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Simulation of Spray Painting Using Articulated – Arm Robot

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ABSTRACT:
Robot trajectory generation for spray painting have highly demand in modern manufacturing. One of the most common surfaces in spray painting operations is ruled surfaces. In this paper, a geometry based spray paint trajectory generation system for ruled surfaces has been developed to simulate the spray painting process using articulated arm robot. The developed system use the geometry information of both the required ruled surface to be painted and the paint spot to generate spray painting trajectory for Labvolt RoboCIM 5150 articulated robot. The developed system designed using Matlab software, and has been simulated and evaluated using the Labvolt system. The results have shown that the generated trajectory achieves satisfactory performance.

Keywords: Robot trajectory planning, Spray painting, Ruled surfaces

محاكاة عملية الصبغ بالنثر باستخدام روبوت ذو ذراع مفصلية

الخلاصة:
يعد موضوع توليد مسارات الروبوت لعملية الصبغ بالنثر من المواضيع المهمة في التصنيع الحديث. أحد اهم السطوح الشائعة في عمليات الصبغ بالنثر هي السطوح المخططة. في هذه المقالة، تم تطوير نظام لتوليد مسارات للروبوت لعملية الصبغ بالنثر بالأعتماد على الهندسية للسطوح المخططة، يعمل هذا النظام على محاكاة عملية الصبغ بالنثر باستخدام روبوت ذو ذراع مفصلية. يستخدم النظام الذي تم تطويره المعلومات الهندسية لكل من السطح المخطط المطلوب صبغه وبقعة الصبغ لتوليد مسار الصبغ لذراع روبوت مفصلية من نوع Labvolt RoboCIM 5150 . تم تصميم النظام باستخدام برنامج الماتلاب ، وتم محاكاته وتقييمه باستخدام نظام الروبوت Labvolt. اظهرت النتائج تحقيقا مقبول الأداء للمسار المتولد.

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INTRODUCTION

The present invention relates generally to an automated manufacturing system and, more particularly, a system and method for planning a tool path along a contoured surface of a Workpiece in an automated manufacturing application. Within the last decade, computer-aided design (CAD) and computer-aided manufacturing (CAM) have been extensively applied in the manufacturing industry. CAD technology is typically used to design one or more parts of a manufactured article. In the manufacturing process, automated robotic equipment is then used to Weld, paint, gauge and assemble the parts into a manufactured article. For instance, a part may be painted using a paint gun that is moved along the surface of the part by a robot. In recent years, there has been a focus on how to use CAD information as a basis for determining the motions of robotic equipment used in the manufacturing process. In particular, it is desirable to use the CAD information to determine the path of the paint gun or the sensor as it moves along the surface of a part. A current approach for planning the path of a tool along the surface of a part requires extensive human involvement. CAM technology may be used to guide the motions of the robotic equipment. In other Words, tool configuration and path planning are programmed by human operator into the controllers of the robotic equipment. As a result, the tool path planning process is time-consuming and prone to error. Therefore, it is desirable to provide an automated system and method for planning a tool path along a surface of a Workpiece in surface-based manufacturing applications. As a result, the set-up time and cost to make a new part can be significantly reduced and thereby improve the quality of the Manufacturing process [1,2]. Developing of a system that plan the trajectory generation for spray painting is very demand to enhance the painting process through minimizing paint waste and process time beside increase the paint quality. Automated trajectory generation for spray painting has been widely studied.

Heping Chen and et al (2002). In this paper, a CAD-guided paint gun trajectory generation system for free-form surfaces has been developed. The system utilizes the CAD information of a

Free-form surface to be painted and a paint gun model to generate a paint gun trajectory to satisfy the paint thickness requirements. A paint thickness verification method is also provided to verify the generated trajectories. The simulation results have shown that the trajectory generation system achieves satisfactory performance [3].

Heping Chen and et al (2004). In this paper, a CADguided chopper gun trajectory planning system with non-uniform material distribution for free-form surfaces is presented. A multi-objective constrained optimization problem is formulated. The simulation results have shown that this system achieves performance required by production applications [4].

Janhavi B. and et al (2010) developed a simulation system of spray painting making use of Microbot Alpha II robot and have used the Open Source Animation software (Blender) to create videos to teach and demonstrate the working of the robot in an industrial environment [5].

The Robot System:

The robot system taken in this work is the Lab-Volt articulated Robot System, which provides complete and affordable training in the programming and operation of industrial robots.It comes with the Robot Software (RoboCIM 5150) which allows controlling or simulating the motion of the Robot, shown in Figure (1)[6].

Kinematics model:

To design a control strategy for the robot arm, research of the mathematics associated with robot kinematics was conducted. Robot kinematics deals with the motion and structure of robot manipulators. There are two particular problems associated with kinematics of robot manipulators

1. Determining the solution of the direct kinematics problem.
2. Determining the solution of the inverse kinematics problem.

For direct kinematics, the joint variable is given and the problem is to find the location of the end effector. For inverse kinematics, the location of the end effector is given and the problem is to find the joint variables necessary to bring the end effector to the desired location. Figure (2) shows a simplified block diagram of kinematics modeling.

Assigning the Coordinate Frames:

Lab_Volt R5150 has robot manipulator with five rotational joints and a moving grip as shown in Figure (3). Joint 1 represents the waist (base) and its axis of motion is z0. This joint provides a rotational θ_1 angular motion around z0 axis in x0y0 plane. Joint 2 is identified as the shoulder and its axis is perpendicular to Joint 1 axis. It provides a rotational θ_2 angular motion around z1 axis in x1y1 plane. z2 axes of Joint 3 (Forearm) and z3 of Joint 4 (Wrist) are parallel to z1 axis of Joint 2; they provide θ_3 and θ_4 angular motions in x2y2 and x3y3 planes respectively. Joint five is identified as the grip rotation. Its z4 axis is vertical to z3 axis and it provides θ_5 angular motions in x4y4 plane. Figure (3) show the robot at rest position (all joint angles equal to zero).

Transformation Matrix:

After establishing (D-H) coordinate system for each link figure(3), a homogeneous transformation matrix can easily be developed considering frame {i-1} and frame {i} transformation consisting of four basic transformations as shown in Table (1) and the joint link parameter as given in Table (2). The overall complex homogeneous matrix of transformation can be formed by consecutive applications of simple transformations according to Denavit- Hartenberg (D-H) notation [8].

The overall (4 x 4) coordinate transformation matrix, T (tool, reference), results from multiplying the individual frame-to-frame (T) matrices together. The entries in the T (tool, reference) matrix will, in general be functions of all 5 joint variables.

$$
{}^{0}T_{1} = \begin{bmatrix} c_{\theta 1} & 0 & s_{\theta 1} & 0 \\ s_{\theta 1} & 0 & -c_{\theta 1} & 0 \\ 0 & 0 & 0 & d1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}T_{2} = \begin{bmatrix} c_{\theta 2} & -s_{\theta 2} & 0 & a_2 c_{\theta 2} \\ s_{\theta 2} & c_{\theta 2} & 0 & a_2 s_{\theta 2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{2}T_{3} = \begin{bmatrix} c_{\theta 3} & -s_{\theta 3} & 0 & a_3 c_{\theta 3} \\ s_{\theta 3} & c_{\theta 3} & 0 & a_3 s_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{3}T_{4} = \begin{bmatrix} c_{\theta 4} & 0 & s_{\theta 4} & 0 \\ s_{\theta 4} & 0 & -c_{\theta 4} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots(1)
$$

$$
{}^{4}T_{5} = \begin{bmatrix} c_{\theta 5} & -s_{\theta 5} & 0 & 0 \\ s_{\theta 5} & c_{\theta 5} & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
{}^{0}T_{5} = {}^{0}T_{1}\ {}^{1}T_{2}\ {}^{2}T_{3}\ {}^{3}T_{4}\ {}^{4}T_{5} = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_x & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \ldots\ldots (2)
$$

The overall transformation matrix has been modeled and simplicity using matlab program as shown in Table (3).From the kinematics modeling equations, we can extract the position and orientation of the end-effector with respect to base.

The general position vector(the tool-tip position) of Lab_volt R5150 is given by ,

$$
\begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \begin{bmatrix} c_1(a_3 c_{23} + a_2 c_2 + d_5 s_{234}) \\ s_1(a_3 c_{23} + a_2 c_2 + d_5 s_{234}) \\ d_1 + a_3 s_{23} + a_2 s_2 - d_5 c_{234} \end{bmatrix} \ldots\ldots\ldots(3)
$$

where

$C_1 = Cos\theta_1$, $S_1 = Sin\theta_1$, $C_{23} = Cos(\theta_2 + \theta_3)$ *and* $S_{23} = Sin(\theta_2 + \theta_3)$

Inverse Kinematic Model:

Inverse Kinematics (IK) analysis determines the joint angles for desired position and orientation of the robot end-effect in Cartesian space, each joint position must therefore be known to obtain the necessary robot motion that achieves the desired end-effect location. The general steps of position control of robot arm are illustrated in Figure (4) as block diagram.

Proposal Approach for Inverse Kinematics:

Inverse Kinematics analysis determines the joint angles for desired position and Orientation in Cartesian space. Total Transformation matrix Equation will be used to calculate inverse kinematics equations. Its solution, however, is much more complex than direct kinematics since there is no unique analytical solution. Each manipulator needs a particular method considering the system structure and restrictions [9]. In the inverse kinematics the user specifies the desired goal position of the end-effector in Cartesian space as (x, y, z) where z is the height of the end effector From figure (5) θ_1 can be calculated from the following equation

θ_1 = Atan2(py,px).

The lengths d_1, a_2, a_3 and d_5 correspond to the shoulder height, upper arm length, forearm length and gripper length, respectively are constant. The angles θ_1, θ_2, θ_3, θ_4 and θ_5 correspond to waist rotation, upper arm, forearm, wrist, and end-effector, respectively. These angles are updated as the specified location in space changes. We solve for the joint angles of the arm, θ1:5 given desired position (x, y, and z) and orientation (Pitch, Roll).

The geometric approach used to solve for these angles, looking at figure (6) concluding that the relationship between θ , θ ,θ and γ as shown below.

$$\gamma = \theta_1 + \theta_2 + \theta_3 \qquad \text{…(4)}$$

Also the calculation of γ can be calculated from the equation 2 as shown below

$$\cos(\gamma) = T(3,3) \qquad \text{…(5)}$$

$$\sin(\gamma) = ataan2(\sqrt{1-\cos(\gamma)^2}\ , -\cos(\gamma))$$

rw=rg - d5cos(γ)

zw=zg - d5 sin(γ)

Or

rw=a2cos(θ) + a3cos(θ + θ)

zw=a2sin(θ) + a3 sin(θ + θ)

$$\cos(\theta_3) = \frac{(zw - d1)^2 + rw^2 - a2^2 - a3^2}{2a2a3}$$

$$\sin(\theta_2) = \sqrt{1 - \cos(\theta_3)^2}$$

$$\theta_3 = a\tan 2(\sin(\theta_3), \cos(\theta_2)) \quad ...(6)$$

$$\theta_2 = a\tan 2((zw - d1), rw) - a\tan 2(a3\sin(\theta_3) + a2 + a3\cos(\theta_3)) \quad ...(7)$$

$$\theta_4 = \gamma - \theta_2 - \theta_3 \quad \ldots(8)$$

Ruled surfaces:

Ruled surface is one of the fundamental elements in industrial surface modelers. It has wide applications because of its simplicity and ease to construct. A ruled surface is a polygon mesh created between two defined boundaries [10, 11].

The objects which can be used to define the boundaries are lines, arcs, circles, points and 2D/3D polylines.

The surface created is a “one-way” mesh of straight lines drawn between the two boundaries. Figure (7) shows types of the ruled surfaces taken in this work.

The implementation:

The general framework for the developed system is shown in Figure (8). The developed system generates spray paint trajectory for a ruled surface depending on the geometric model for the ruled surface, and using the diameter of the paint spot which is commonly take a circular model.

The developed system, which is written using Matlab software, is produce a trajectory for Robot manipulator (Labvolt RoboCIM 5150) based on the geometrical and operational parameters of the robot system.

In this work, two cases have been taken to cover the common forms of ruled surfaces which are useful in spray painting operations. The two ruled surfaces have been drawn using CAD system, then imported by Matlab based software developed for this purpose.

The developed software takes the inverse kinematic for the Cartesian coordinates of the taken surfaces; the Joint coordinates have been calculated and used to move the robot arm to accomplish the required trajectory of spray painting.

Given the position and the orientation of each point of the surface, inverse kinematic analysis is performed on the developed software system and delivered to the RoboCIM 5150 robot system to determine the vector of joint variables or kinematic parameters for the robot arm to accomplish the given position coordinates of the ruled surface.

In this work, the robot is stationary. It end effecter is placed parallel to the surface being painted. The spray paint tool is attached to the end effecter.

The Results:

The developed system handled two cases of ruled surfaces, shown in Table 4 and 5 which present the Cartesian coordinate of the taken ruled surface and its joint coordinates after implementing the inverse kinematic. These results have been verified through the application of the joint coordinates, calculated from the developed system by inverse kinematic; into the robot system software to simulate the motion of robot end effecter and the motion accomplish the entire paint path efficiently, Figure (9) shows side of the implementation.

Conclusion:

A geometric based paint tool trajectory generation system for ruled surface has been developed using Matlab software. Simulation results using Robot system showed that the paint trajectory requirements are satisfied.

This method could be used as an off-line trajectory generation system for ruled surfaces for spray painting using articulated robot system.

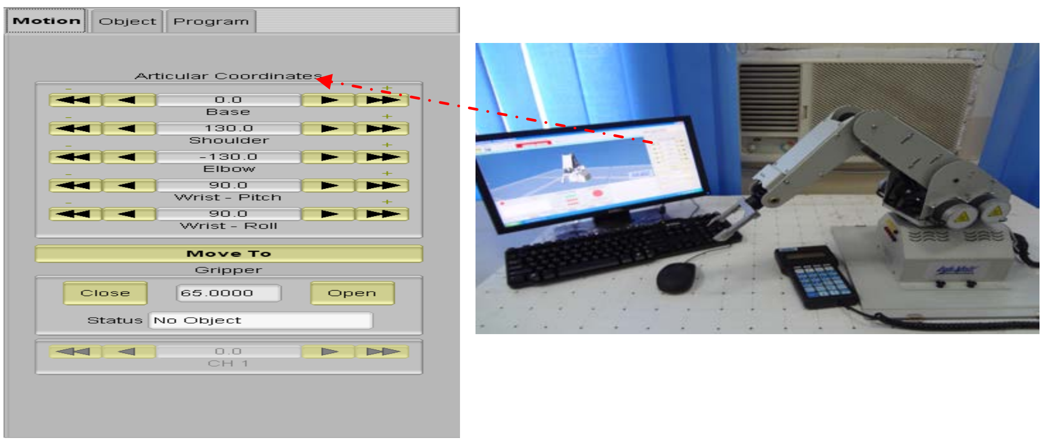

Figure (1): Lab volt R5150 Robot Manipulator System

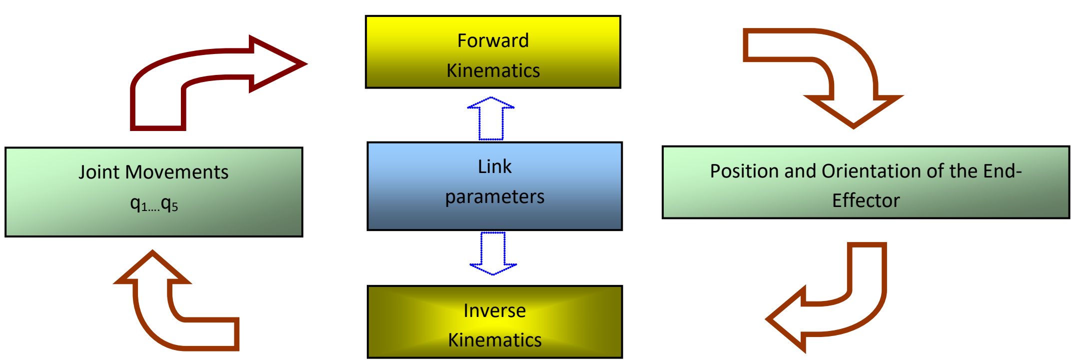

Figure (2): kinematics Block Diagram

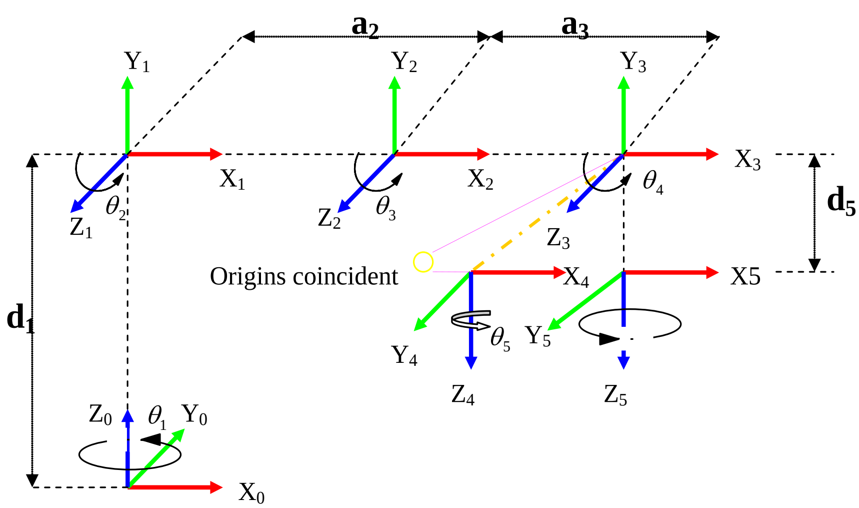

Figure (3): Link Coordinates of a Five_Axis Robot Manipulator [7].

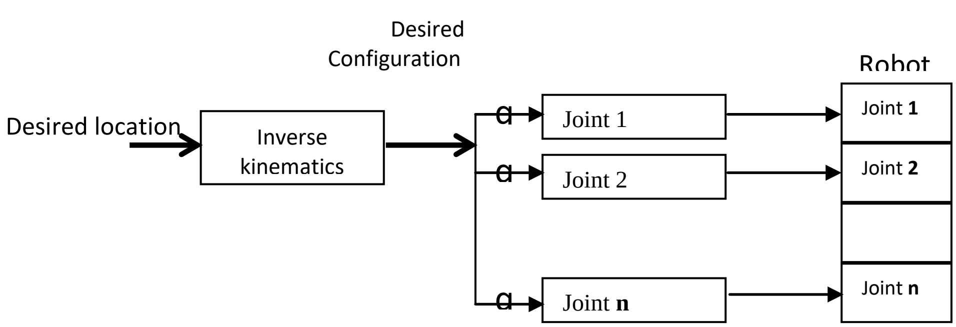

Figure (4): location Control of a Robot Arm

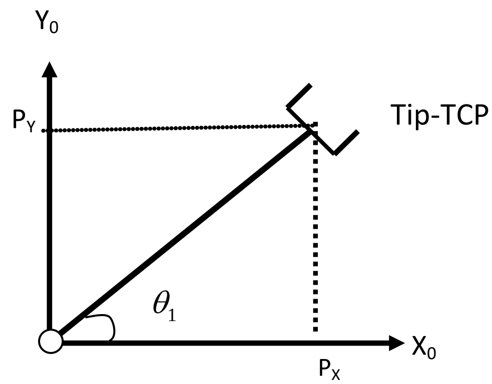

Figure (5): Geometric Analysis

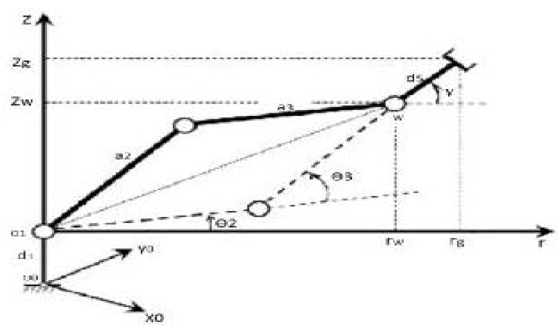

Figure (6): Arm Articulator planar view of robot[9]

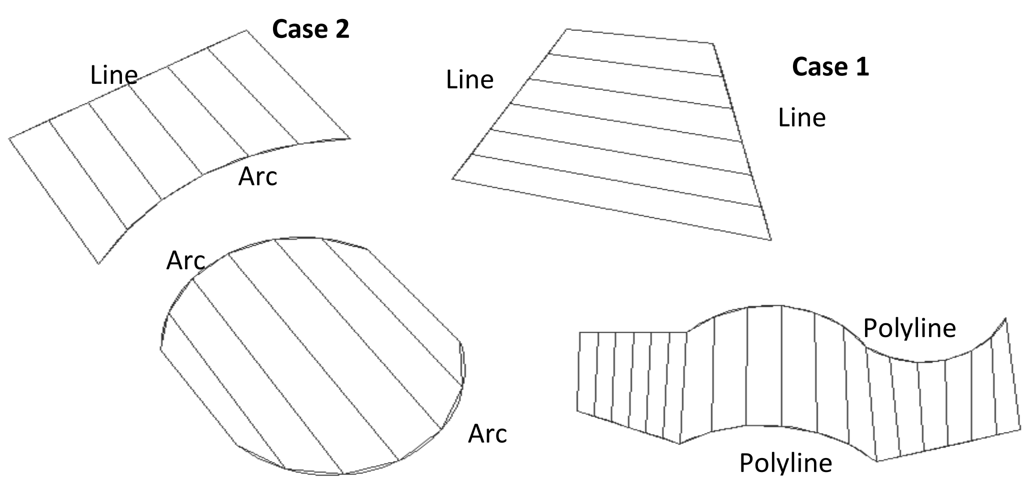

Figure (7): The taken ruled surface types.

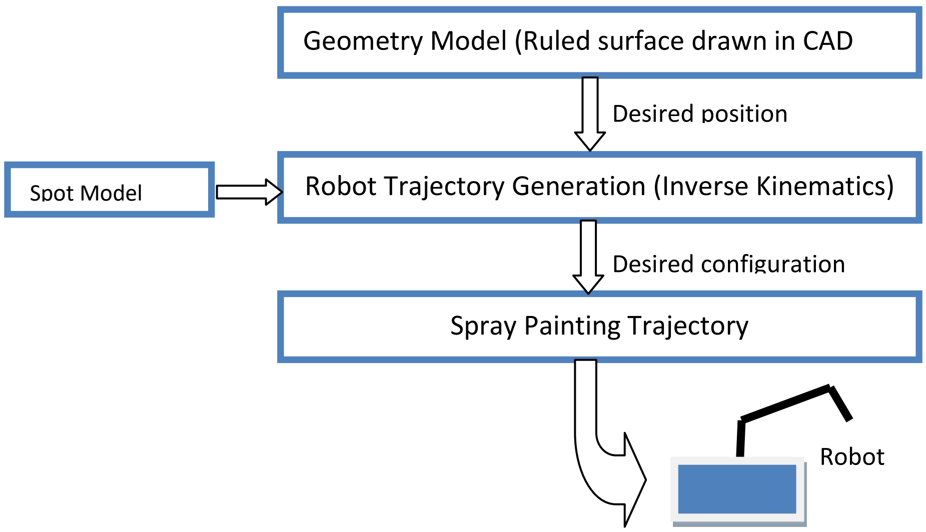

Figure (8): Geometry-based spray paint trajectory generation system.

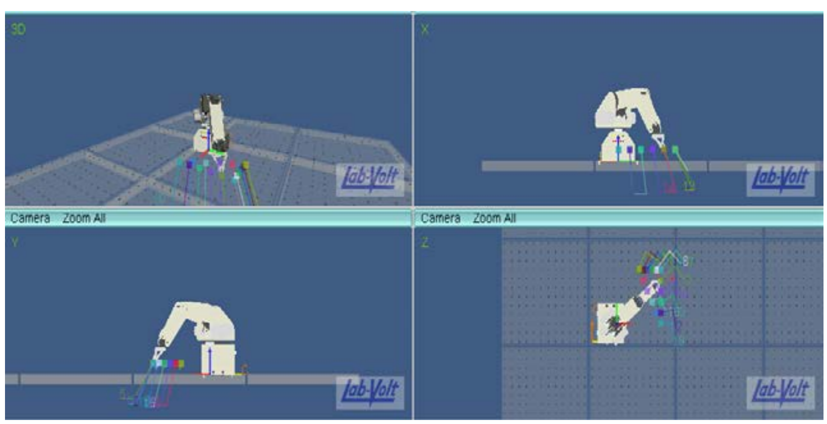

Figure (9): Side of the implementation part of the work (simulation phase)

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

Operation	Description
$\mathbf{T_1}$	A rotation about z_{i-1} axis by an angle θ_i.
$\mathbf{T_2}$	Translation along z_{i-1} axis by distance $d_{i.}$
$\mathbf{T_3}$	Translation by distance a_i along x_i axis

T_4	Rotation by angle α_i about x_i axis

Table (3): Kinematics Equations from the Overall Transformation Matrix.

Equation No	RHS	LHS	Vector	Component
1	nx	$c_1c_{234}c_5 + s_1s_5$		X
2	ny	$s_1s_{234}c_5 - c_1s_5$	normal vector	Y
3	nz	$s_{234}c_5$		Z
4	ox	$s_1c_5 - c_1c_{234}s_5$		X
5	oy	$-s_1c_{234}s_5 - c_1c_5$	orientation vector	Y
6	oz	$-s_{234}s_5$		Z
7	ax	c_1s_{234}		X
8	ay	s_1s_{234}	approach vector	Y
9	az	$-c_{234}$		Z
10	px	$c_1(a_3c_{23} + a_2c_2 + d_5s_{234}$		X
11	py	$s_1(a_3c_{23} + a_2c_2 + d_5s_{234}$	position vector	Y
12	pz	$d_1 + a_3s_{23} + a_2s_2 - d_5c_{234}$		Z

where:

n : Normal vector of the hand. Assuming a parallel-jaw hand, it is orthogonal to the fingers of the robot arm.

o : Orientation vector(Sliding vector)of the hand. It is pointing in the direction of the finger motion as the gripper opens and closes.

a : Approach vector of the hand. It is pointing in the direction normal to the palm of the hand (i.e., normal to the tool mounting plate of the arm).

p : Position vector of the hand. It points from the origin of the base coordinate system to the origin of the hand coordinate system, which is usually located at the center point of the fully closed fingers.

The orientation of the hand is described according to the Euler (RPY) rotation as:

The orientation of the hand is described according to the Euler (RPY) rotation as:

$$RPY(\psi_Z, \psi_Y, \psi_X) = Rot(x, \psi_X).Rot(y, \psi_Y).Rot(z, \psi_Z) \quad \text{…..(9)}$$

Table (2) D-H Parameter for R5150 Robot Arm [7].

Axis	joint name	θ_i	d_i (mm)	a_i (mm)	α_i	range θ_i	motion
1	base	θ_1	255.55	0	90	-185 to +153	rotates the body
2	shoulder	θ_2	0	190	0	-32 to +149	raises and lowers (upper arm)
3	elbow	θ_3	0	190	0	-147 to +51	raises and lowers (forearm)
4	Tool pitch	θ_4	0	0	90	-5 to 180	raises and lowers (gripper)
5	Tool roll	θ_5	115	0	0	± 360	rotates the gripper

Table . (4): Sample of coordinates for case 1. This is shown in Figure (7).

#	Cartesian coordinates			Joint Coordinates				
	X (mm)	Y(mm)	Z(mm)	q5	q4	q3	q2	q1
1	150	58.6357	-123.2727	64.6370	33.6901	150	100	90
2	150	26.3787	-55.9851	29.6064	63.4349	150	300	90
3	180	22.6238	-51.7705	29.1467	58.1726	160	290	90
4	180	50.8499	-112.2357	61.3857	31.4296	160	110	90
5	210	43.1768	-100.2380	57.0612	29.7449	170	120	90
6	210	17.6261	-44.8717	27.2456	53.1301	170	280	90
7	240	10.7679	-34.0003	23.2324	48.3665	180	270	90
8	240	35.2449	-86.9383	51.6934	28.4429	180	130	90
9	270	26.5837	-71.6373	45.0536	27.4076	190	140	90
10	270	-1.7549	-11.5209	13.2758	43.9191	190	260	90

Table (5): Sample of coordinates for case 2. This is shown in Figure (7).

#	Cartesian coordinates			Joint Coordinates				
	X (mm)	Y(mm)	Z(mm)	q5	q4	q3	q2	q1
1	172	162	300	43.69	96.24	-116.44	64.31	0
2	300	162	300	28.43	66.30	-81.62	59.70	0
3	192	182	300	43.42	88.24	-108.14	64.73	0
…								
10	300	255.4	300	40.41	49.41	-55.01	50.59	0

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