Modeling and Simulation of 5 DOF Educational Robot Arm

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***Abstract* - Many universities and institutes experience difficulty in training people to work with expensive equipments. A common problem faced by educational institutions concerns the limited availability of expensive robotics equipments, with which students in the didactic program can work, in order to acquire valuable "hands on" experience. Therefore, the Robot Simulation Software (RSS) nowadays is paramount important.**

This paper presents the development of a visual software package where a AL5B Robot arm has been taken as a case study. It utilizes Matlab/Simulink and AutoCAD as the tools for testing motional characteristics of the AL5B Robot arm. A robot model will be developed; the Forward, Inverse Kinematics, Velocity Kinematics "Jacobian" and Path Planning problems will be implemented and tested.

The developed package will be used as an educational tool. We think that this work will increase the education, training, research and development possibilities for robotics classes in graduate and under graduate studies.

Keywords: Modeling, Simulation, MATLAB/Simulink, 5DOF Robot arm, Forward Kinematics, IK, Path Planning, Jacobian.

I. INTRODUCTION

Robotics is a relatively young field of modern technology that crosses traditional engineering boundaries. Understanding the complexity of robots and their applications requires knowledge of electrical engineering, mechanical engineering, systems and industrial engineering, computer science, economics, and mathematics. New disciplines of engineering, such as manufacturing engineering, applications engineering, and knowledge engineering have emerged to deal with the complexity of the field of robotics and factory automation [1].

This paper is concerned with the fundamentals of robotics, including kinematics, motion planning, Jacobian, interface and control. Our goal is to introduce the most important concepts in these subjects as applied to industrial robot manipulators, mobile robots, and other mechanical systems. A complete treatment of the discipline of robotics would require several volumes. Nevertheless, now, the majority of robot applications deal with industrial robot arms operating in structured factory environments so that a first introduction to the subject of robotics must include a rigorous treatment of the topics in this paper.

There is a large amount of literature which discuss the robot molding and analysis of industrial robots [2]. The majority of their importance comes from discussing the low cost educational robot arms. Therefore, in this paper, mathematical model and kinematical analysis of the AL5B educational robot arm shown in Fig. 1 will be studied.

A visual software program will be also developed to show the robot arm motion with respect to its mathematical analysis

Figure 1. AL5B robotic arm

This paper presents the development of a visual model for the AL5B robot arm to be use educational institution in Gaza Strip to teach robotic courses.

The paper is organized as follow: section II gives a full description of AL5B robot arm, section III gives the complete kinematic modeling, section IV covers the software, section V gives the results, and section VI concludes this paper.

II. ROBOT DESCRIPTION

AL5B robot arm has 5 directions of motion (DOF) plus a grip movement (5+1). It is also similar to human arm from the number of joints point of view. These joints provide shoulder rotation, shoulder back and forth motion, elbow motion, wrist up and down motion, wrist rotation and gripper motion.

AL5B has five rotational joints and a moving grip. Joint 1 represents the shoulder and its axis of motion is z1. This joint provides a rotational θ1 angular motion around z1 axis in x1y1 plane. Joint 2 is identified as the Upper Arm and its axis is perpendicular to Joint 1 axis. It provides a rotational θ2 angular motion around z2 axis in x2y2 plane. z3 axes of Joint 3 (Forearm) and Joint 4 (Wrist) are parallel to Joint 2 z-axis; they provide θ3 and θ4 angular motions in x3y3 and x4y4 planes respectively. Joint five is identified as the grip rotation. Its z5 axis is vertical to z4 axis and it provides θ5 angular motions in x5y5 plane. A graphical view of all the joints was displayed in Fig. 2.

A rigid body is completely described in space by its position to a reference frame (translation) and its orientation.

AL5B Robot Arm rotational joints and the grip are controlled by dedicated servo motors. These motors are connected to a serial servo controller card Cubloc (CB280) to control the AL5B from a computer through the serial port.

A sequence of 3 consecutive unsigned bytes is sent to serial servo controller from the computer. These are the default sync byte, the joint servo identifier byte and the desired position byte. Rotational position of a servo motor is determined by a specific angle by closed loop feedback. This angle value, provided by the computer, was digitized to generate discrete motional steps by the CB280 card.

CB280 servo control card provides the hardware interface between computer and the robot arm. It has a time resolution of 1µs for accurate positioning and a dc motor control to generate extremely smooth moves. The time range is 0.50mS to 2.50mS for an angular range of 0° to 180°. The card generated motion can be a speed controlled, time controlled or a combination (speed and time) motion.

III. KINEMATICS

Many methods can be used in the direct kinematics calculation. The Denavit-Hartenberg 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 [3].

D-H parameters for AL5B are defined for the assigned frames in Table I. For example Frame 5 is the grip frame with attached end effectors at joint 5.

TABLE I. DH PARAMETER FOR AL5B ROBOT ARM

i	α_{i-1}	a_{i-1}	d_i	θ_i
1	0	0	d_1	θ_1^{*}
2	90	0	0	θ_2^{*}
3	0	a_3	0	θ_3^{*}
4	0	a_4	0	θ_4 -90*
5	-90	0	d_5	θ_5^{*}
6	0	0	0	*Gripper*

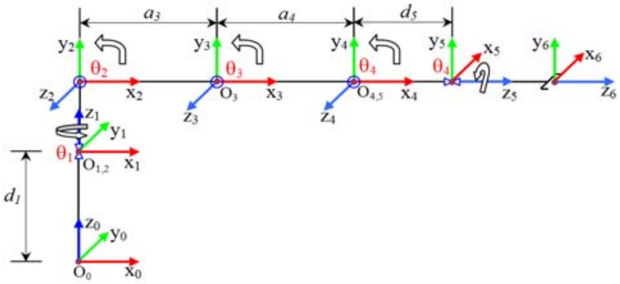

Figure 2. Coordinate Frames of AL5B Robotic Arm

By substituting these parameters; the transformation matrices T1 to T6 can be obtained as shown bellow. For example, T1 shows the transformation between frames 0 and 1 (designating Ci as cos θi and Si as sin θi etc).

$$T_1^0 = \begin{bmatrix} c_{\theta_1} & -s_{\theta_1} & 0 & 0 \\ s_{\theta_1} & c_{\theta_1} & 0 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_2^1 = \begin{bmatrix} c_{\theta_2} & -s_{\theta_2} & 0 & 0 \\ 0 & 0 & -1 & 0 \\ s_{\theta_2} & c_{\theta_2} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_3^2 = \begin{bmatrix} c_{\theta_3} & -s_{\theta_3} & 0 & a_3 \\ s_{\theta_3} & c_{\theta_3} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_4^3 = \begin{bmatrix} c_{\theta_4} & -s_{\theta_4} & 0 & a_4 \\ s_{\theta_4} & c_{\theta_4} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_5^4 = \begin{bmatrix} c_{\theta_5} & -s_{\theta_5} & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ s_{\theta_5} & c_{\theta_5} & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad T_{Gripper} = \begin{bmatrix} c_{\theta_5} & -s_{\theta_5} & 0 & 0 \\ s_{\theta_5} & c_{\theta_5} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

A. *Forward Kinematic*

Calculating the position and orientation of the end effectors with given joint angles is called Forward Kinematics analysis. Forward Kinematics equations are generated from the transformation matrixes shown bellow and the forward kinematics solution of the arm is the product of these six matrices identified as ${}^0T_6$ (with respect to base) shown in eq.(1)

$$T_6^0 = T_1^0 T_2^1 T_3^2 T_4^3 T_5^4 T_6^5 = \begin{bmatrix} n_x & o_x & a_x & d_x \\ n_y & o_y & a_y & d_y \\ n_z & o_z & a_z & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

The first three columns in the matrices represent the orientation of the end effectors, whereas the last column represents the position of the end effectors [3]. The orientation and position of the end effectors can be calculated in terms of joint angles.

B. *Invers Kinematic*

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 [4].

Geometric Approach

Using IK-Cartesian mode, the user specifies the desired target position of the gripper in Cartesian space as (x, y, z) where z is the height, and the angle of the gripper relative to ground, ψ (see Fig.4, is held constant. This constant ψ allows users to move objects without changing the object's orientation (the holding a cup of liquid scenario). In addition, by either keeping ψ fixed in position mode or keeping the wrist fixed relative to the rest of the arm, the inverse kinematic equations can be solved in closed form as we now show for the case of a fixed ψ.

The lengths d_1, a_3, a_4 and d_5 correspond to the base height, upper arm length, forearm length and gripper length, respectively, and are constant [4], [5]. The angles θ_1, θ_2, θ_3, θ_4 and θ_5 correspond to shoulder rotation, upper arm, and forearm, wrist, and End effectors, respectively. These angles are updated as the specified position in space changes. We solve for the joint angles of the arm, $\theta_{1:4}$ given desired position (x, y, and z) and ψ which are inserted by the user.

From Fig. 3, we clearly see that $\theta_1 = \mathrm{Atan2}(y, x)$ and the specified radial distance from the base d are related to x and y by:

$$d = \sqrt{x_d^{\,2} + y_d^{\,2}} \tag{2}$$

$$x_d = d\cos(\theta_1) \tag{3}$$

$$y_d = d\sin(\theta_1) \tag{4}$$

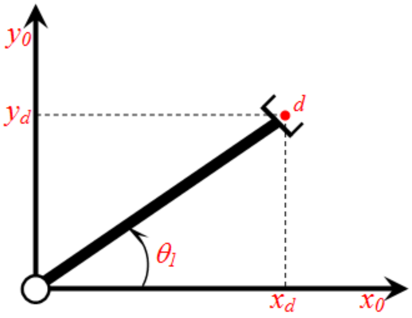

Figure 3. AL5B Geometric analysis

Moving now to the planar view in Fig. 4, we find a relationship between joint angles θ_2, θ_3 and θ_4 and ψ as follows:

$$\psi = \theta_2 + \theta_3 + \theta_4 \tag{5}$$

Since ψ is given, we can calculate the radial distance and height of the wrist joint:

$$r_4 = r_d - a_5\cos(\psi) \tag{6}$$

$$z_4 = z_d - a_5\sin(\psi) \tag{7}$$

or

$$r_4 = a_3\cos(\theta_2) + a_4\cos(\theta_2 + \theta_3) \tag{8}$$

$$z_4 = a_3\sin(\theta_2) + a_4\sin(\theta_2 + \theta_3) + d_1 \tag{9}$$

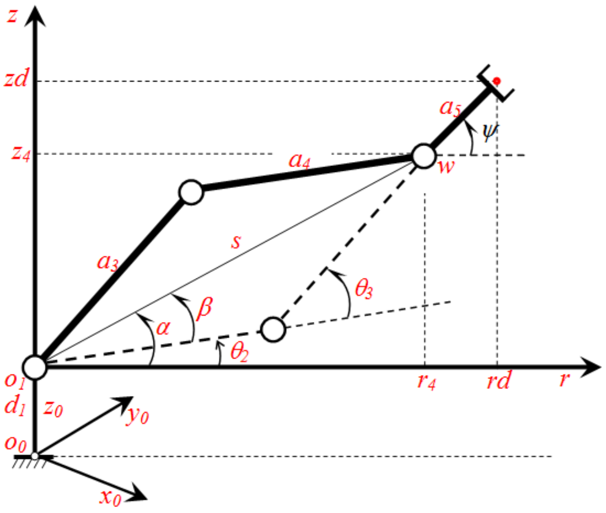

Figure 4. Arm sagittal planar view of robot

Now we want to determine θ_2 and θ_3. We first solve for α, β and s (from Fig. 3B) uses the law of cosines as:

$$\beta = A\tan 2(s^2 + a_3^{\,2} - a_4^{\,2}, 2sa_3) \tag{10}$$

$$\alpha = A\tan 2(z_4 - d_1, r_4) \tag{11}$$

$$s = \sqrt{(z_4 - d_1)^2 + r_4^{\,2}} \tag{12}$$

With these intermediate values, we can now find the remaining angle values as:

$$\theta_2 = \alpha \pm \beta \tag{13}$$

$$\theta_3 = A\tan 2(s^2 - a_3^2 - a_4^2, 2a_3a_4) \tag{14}$$

$$\theta_4 = \psi - \theta_2 - \theta_3 \tag{15}$$

C. *Velocity Kinematics/Arm Jacobian*

The Jacobian is one of the most important quantities in the analysis and control of robot motion. It is used for smooth trajectory planning and execution in the derivation of the dynamic equation. To investigate target with specified velocity, each joint velocity at the specified joint positions needs to be found. This is accomplished using Jacobian, which are used to relate joint velocities to the linear and angular velocities of the end-effector. For the AL5B robot arm the Jacobian matrix is equal 6x5

$$J(q) = \begin{bmatrix} z_0 \times (o_5 - o_0) & z_1 \times (o_5 - o_1) & z_2 \times (o_5 - o_2) & z_3 \times (o_5 - o_3) & z_4 \times (o_5 - o_4) \\ z_0 & z_1 & z_2 & z_3 & z_4 \end{bmatrix} \tag{16}$$

From the forward kinematic we can find:

$$o_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, o_1 = \begin{bmatrix} 0 \\ 0 \\ d1 \end{bmatrix}, o_2 = \begin{bmatrix} 0 \\ 0 \\ d1 \end{bmatrix}, o_3 = \begin{bmatrix} c_1c_2a_3 \\ c_1s_1a_3 \\ s_2a_3 + d_1 \end{bmatrix}$$

$$o_4 = \begin{bmatrix} c_1c_{23}a_4 + c_1c_2a_3 \\ s_1c_{23}a_4 + s_1c_2a_3 \\ s_{23}a_4 + s_2a_3 + d_1 \end{bmatrix}, o_5 = \begin{bmatrix} c_1c_{234}d_5 + c_1c_{23}a_4 + c_1c_2a_3 \\ s_1c_{234}d_5 + s_1c_{23}a_4 + s_1c_2a_3 \\ s_{234}d_5 + s_{23}a_4 + s_2a_3 + d1 \end{bmatrix}$$

Moreover, we can find:

$$z_0 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, z_1 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, z_2 = \begin{bmatrix} s_1 \\ -c_1 \\ 0 \end{bmatrix}, z_3 = \begin{bmatrix} s_1 \\ -c_1 \\ 0 \end{bmatrix}, z_4 = \begin{bmatrix} s_1 \\ -c_1 \\ 0 \end{bmatrix}, z_5 = \begin{bmatrix} c_1 c_{234} \\ s_1 c_{234} \\ -s_{234} \end{bmatrix}$$

$$J(q) = \begin{bmatrix} J_1 & J_2 & J_3 & J_4 & J_5 \end{bmatrix} \tag{17}$$

$$J_1 = \begin{bmatrix} -s_1 c_{234} d_5 - s_1 c_{23} a_4 - s_1 c_2 a_3 \\ c_1 c_{234} d_5 + c_1 c_{23} a_4 + c_1 c_2 a_3 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, J_2 = \begin{bmatrix} -s_1 c_{234} d_5 - s_1 c_{23} a_4 - s_1 c_2 a_3 \\ c_1 c_{234} d_5 + c_1 c_{23} a_4 + c_1 c_2 a_3 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$J_3 = \begin{bmatrix} -c_1 (s_{234} d_5 + s_{23} a_4 + s_2 a_3) \\ -s_1 (s_{234} d_5 + s_{23} a_4 + s_2 a_3) \\ s_1 (s_1 c_{234} d_5 + s_1 c_{23} a_4 + s_1 c_2 a_3) + c_1 (c_1 c_{234} d_5 + c_1 c_{23} a_4 + c_1 c_2 a_3) \\ s_1 \\ -c_1 \\ 0 \end{bmatrix}$$

$$J_4 = \begin{bmatrix} -c_1 (s_{234} d_5 + s_{23} a_4) \\ -s_1 (s_{234} d_5 + s_{23} a_4) \\ s_1 (s_1 c_{234} d_5 + s_1 c_{23} a_4) + c_1 (c_1 c_{234} d_5 + c_1 c_{23} a_4) \\ s_1 \\ -c_1 \\ 0 \end{bmatrix},$$

$$J_5 = \begin{bmatrix} -c_1 s_{234} d_5 \\ -s_1 s_{234} d_5 \\ s_1^2 c_{234} d_5 + c_1^2 c_{234} d_5 \\ s_1 \\ -c_1 \\ 0 \end{bmatrix}$$

D. Trajectory Planning

Trajectory planning approximate the desired path by a class of polynomial functions and generates a sequence of time-based “control set points” for the control of manipulator from the initial configuration to its destination Fig. 4 shows the Trajectory planning block diagram.

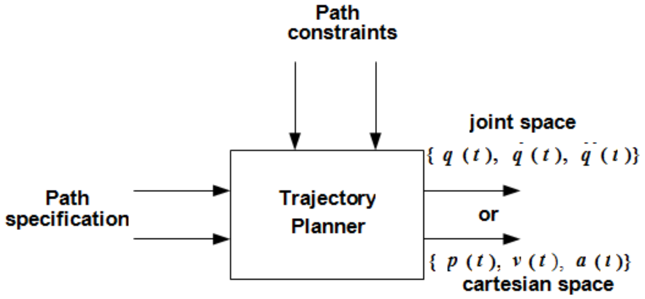

Figure 5. Trajectory planning block diagram

Cubic Polynomial Trajectories

Suppose that we wish to generate a trajectory between two configurations, and that we wish to specify the start and end velocities for the trajectory [1]. If we have four constraints to satisfy, such as following equation we require a polynomial with four independent coefficients that can be chosen to satisfy these constraints. Thus, we consider a cubic trajectory of the form

$$q(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 \qquad \text{For Distance} \tag{18}$$

Then the desired velocity is given as

$$\dot{q}(t) = a_1 + 2a_2 t + 3a_3 t^2 \qquad \text{For Velocity} \tag{19}$$

$$\ddot{q}(t) = 2a_2 + 6a_3 t \qquad \text{For Acceleration} \tag{20}$$

Combining above equations with the four constraints yields four equations in four unknowns

$$q_0 = a_0 + a_1 t_0 + a_2 t_0^2 + a_3 t_0^3 \tag{21}$$

$$v_0 = a_1 + 2a_2 t_0 + 3a^3 t_0^2 \tag{22}$$

$$q_f = a_0 + a_1 t_f + a_2 t_f^2 + a_3 t_f^3 \tag{23}$$

$$v_f = a_1 + 2a_2 t_f + 3a_3 t_f^2 \tag{24}$$

These four equations can be combined into a single matrix equation

$$\begin{bmatrix} 1 & t_0 & t_0^2 & t_0^3 \\ 0 & 1 & 2t_0 & 3t_0^3 \\ 1 & t_f & t_f^2 & t_f^3 \\ 0 & 1 & 2t_f & 3t_f^2 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} q_0 \\ v_0 \\ q_f \\ v_f \end{bmatrix} \tag{25}$$

IV. SOFTWARE

The first step in this process is to design the arm in AutoCAD 3D program. The program chosen for this was Autodesk Inventor. Inventor allows the arm to be designed and visualized at the same time. It also allows the arm to be checked for possible collisions and link interference. Because each link depends upon the previous link, the design of the arm needs to begin at the base and finish at the end effector or gripper. Trunk or base is therefore the first to be designed, followed by shoulder, and so on [6]. This means that the design process is fairly involved, as each link has to be redesigned several times. After we finished the graphics design by using the AutoCAD 3D the main question is how to connect it to MATLAB. We use the CAD2Matlab function, where this function takes a CAD file in (.stl or .slp format) and converts it to Matlab [7]. We need to use anther program to convert the AutoCAD dwg to slp file like PolyTrans 3D from Okino Computer Graphics, by using this program we can modifying the robot link and coordinate and save the file as slp.

Software package was developed to compute the forward kinematics, inverse kinematics, Jacobian, trajectory planning, of AL5B Robot arm. GUI Development Platform with MatLab programming language was used for implementation. An On-line motional simulator of the robot arm was also included of GUI to show the generated motion in Fig. 7 based on the theoretical analysis presented in this paper.

V. RESULTS AND DISCUSSIONS

Mathematical modeling and kinematic analysis of AL5B, was developed and tested in this study. Robot arm was mathematically modeled with Denavit Hartenberg (D-H) method. Forward, Inverse Kinematics, Jacobian and path planning solutions were generated and implemented by the developed software.

After testing the forward kinematic as example for the desired position x, y and z (199.3, 199.3, 154.9) the input angles $\theta_{(1, 2, 3, 4, 5)}$ equal (45, 45,-45, 0, 0) and Vis versa for inverse kinematic as shown in Fig. 7.

Fig. 6 shows the Cubic trajectory playing first three angles with respect to the base.

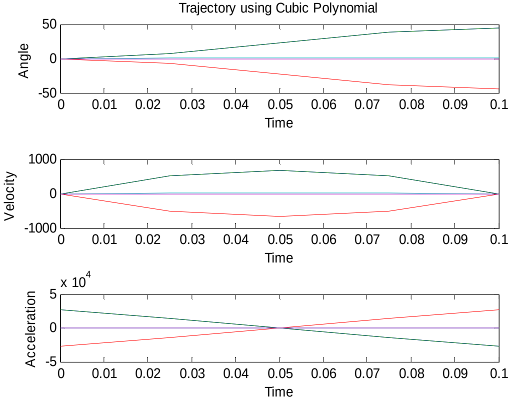

Figure 6. Cubic polynomial trajectory

VI. CONCLUSIONS

A complete Kinematics analysis of the AL5B robot arm was investigated. Graphical User Interface (GUI) was developed to test and simulate the motional characteristics of the Robot arm. A physical interface between the AL5B robot arm and the GUI will be designed.

The developed system will be identified as an educational experimental tool; it can be used in graduate and undergraduate robotic courses to realize the relationships between theoretical and practical aspects of robot manipulator motions in real time.

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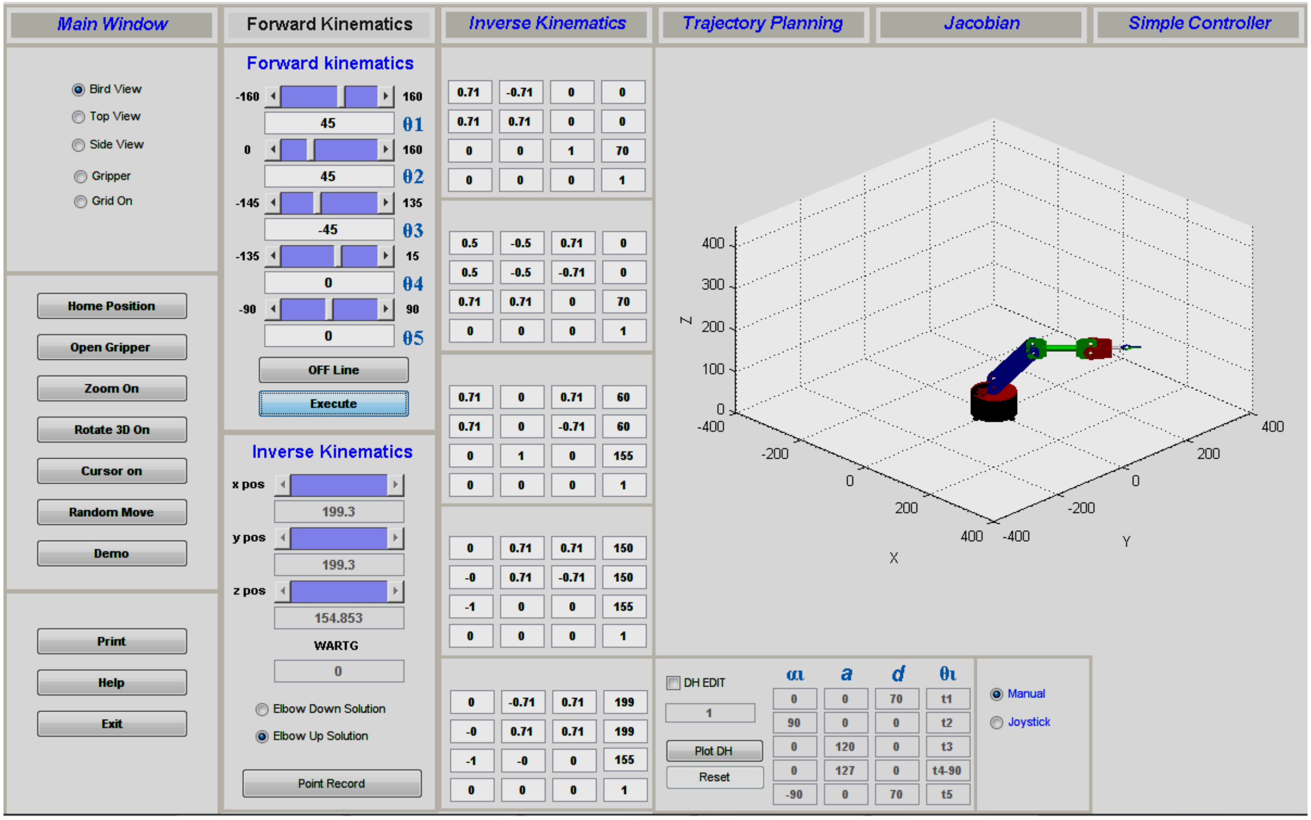

● Bird View
○ Top View
○ Side View
○ Gripper
○ Grid On

Forward kinematics

-160 … 160: θ1 = 45

0 … 160: θ2 = 45

-145 … 135: θ3 = -45

-135 … 15: θ4 = 0

-90 … 90: θ5 = 0

Inverse Kinematics

x pos: 199.3

y pos: 199.3

z pos: 154.853

WARTG: 0

○ Elbow Down Solution

● Elbow Up Solution

0.71	-0.71	0	0
0.71	0.71	0	0
0	0	1	70
0	0	0	1

0.5	-0.5	0.71	0
0.5	-0.5	-0.71	0
0.71	0.71	0	70
0	0	0	1

0.71	0	0.71	60
0.71	0	-0.71	60
0	1	0	155
0	0	0	1

0	0.71	0.71	150
-0	0.71	-0.71	150
-1	0	0	155
0	0	0	1

0	-0.71	0.71	199
-0	0.71	0.71	199
-1	-0	0	155
0	0	0	1

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αι	a	d	θι
0	0	70	t1
90	0	0	t2
0	120	0	t3
0	127	0	t4-90
-90	0	70	t5

● Manual
○ Joystick

Figure 7. GRAPHICAL USER INTERFACE