

# RoboAnalyzer: Robot Visualization Software for Robot Technicians

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## ABSTRACT

Robots have become an irreplaceable part of various industries which has led to an increasing demand for well-trained robot operators or technicians to operate and maintain these robots. The concepts of robotics are difficult to understand from pure mathematical standpoint which has led to the development of various robot visualization software for better understanding of the robot motion. RoboAnalyzer is one such software. In this paper, the features of RoboAnalyzer and how they can be used to teach robotics concepts to robot technicians are discussed.

## CCS Concepts

• **Computer systems organization** → **Embedded and cyber-physical systems** → **Robotics** • **Software and its engineering** → **Software organization and properties** → **Contextual software domains** → **Virtual worlds software** → **Virtual worlds training simulations** • **Applied computing** → **Education** → **Interactive learning environments**

## Keywords

DH Parameters; Forward Dynamics; Forward Kinematics; Inverse Kinematics; Robot Visualization Software

## 1. INTRODUCTION

With the increasing market in the modern world, demand for industrial automation is growing with which the use of robots in the industry is also growing. Usage of the industrial robots has reached almost all industries including automobile, electronics, space, etc. With this increase in the robots, the necessity for the robot technicians to operate and maintain these robots has increased.

Conventional methods to learn robotics requires a deep understanding of mathematical equations, coordinate frame transformations, etc. These concepts are generally difficult to understand for a robot technician, so as to develop a good visualization on the working of the robot. Also, most industrial robots can be described geometrically by their Denavit-Hartenberg (DH) parameters, which are difficult to perceive by using only conventional methods. Hence, a robot visualization software is needed to ensure easier and better understanding of robots by the robot technicians.

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A number of robot visualization software are available in the market and research domain, both free and paid. A brief overview of these tools may be found in [1]. Beside these tools, one can also find many advanced robot visualization tools such as RVS4W [2] and ROBOMOSP [3] which have the ability to perform forward kinematics, inverse kinematics and trajectory planning. RoKiSim [4] is another such product which provides the user with abilities to open 3D CAD models of various industrial robots and control them using joint-level or Cartesian-level jogging. It also provides a module for easy visualization of DH parameters.

RoboAnalyzer is another such software. It is a 3D-model based robot visualization software which can model serial robots using their DH parameters. It has capabilities to perform forward kinematics, inverse kinematics, inverse and forward dynamics of robots, and some trajectory planning. The output is available in various forms including animations, graph plots, etc. A virtual robot simulator module is also available in the package which allows a user to move a robot using various modes as one would do when using a teach pendant. One of its key feature is that it allows the user to visualize multiple solutions of inverse kinematic analysis by allowing the user to observe the motion between any two possible solutions [5].

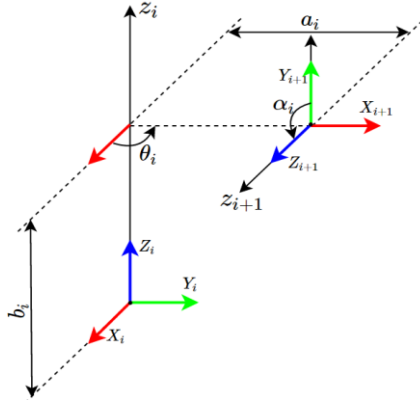
This paper focuses on how a robot visualization software is useful for a robot technician working in an industry and how it can be used effectively to improve work efficiency in those industries. In this paper, modules on ‘Visualization of DH Parameters’, ‘Forward Kinematics’, ‘Inverse Kinematics’ and ‘Inverse Dynamics’ are presented. In the first module, user learns how to visualize DH parameters using a virtual robot. In the second, user loads the DH parameters in a robot visualization software to help him/her visualize the motion of the robot in a 3D space. In third module, user gets to know what multiple pathways are possible to reach the same end-effector pose and how they are related to each other. In the last module, user gets to know the effect of the path and payload on the motor torques.

## 2. DENAVIT-HARTENBERG (DH) PARAMETERS

Most industrial robot have a serial architecture which consists of several links connected to each other through a single degree-of-freedom (DOF) joint. These joints can be prismatic (P) or revolute (R) type. To understand the effect of the joint motions on the final pose of the robot, it is necessary to have correlation between the coordinate frames attached to the end-effector and the base of the robot. To facilitate this correlation, a DH frame is attached to each link which is related to the previous DH frame using four DH parameters (Figure 1, Table 1). The rules to attach these frames to the links are explained in [6].

**Table 1: Description of DH Parameters**

Parameters	Description
Joint Offset ( $b_i$ )	Distance between $X_i$ and $X_{i+1}$ along $Z_i$
Joint Angle ( $\theta_i$ )	Angle between $X_i$ and $X_{i+1}$ about $Z_i$
Link Length ( $a_i$ )	Distance between $Z_i$ and $Z_{i+1}$ along $Z_{i+1}$
Twist Angle ( $\alpha_i$ )	Angle between $Z_i$ and $Z_{i+1}$ along $Z_{i+1}$



**Figure 1: Denavit-Hartenberg (DH) parameters**

## 2.1 Measurement of DH parameters

Most industrial robots are designed such that a plane could be defined in which the end-effector moves and this plane is then rotated about the base axis to create a 3D workspace for the robot. In the identification of DH parameters, one of the first step is to identify this plane. Once this plane is known, measurement of DH parameters becomes a simple task of measurement of appropriate lengths and angles in the plane.

The DH parameters measurement methodology is explained below by considering KUKA KR5 Arc robot as example:

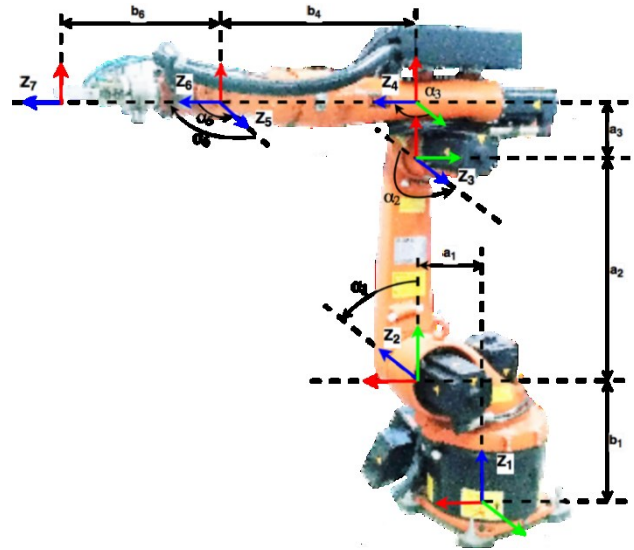
1. Attach a coordinate system or frame 1 on the base link (Link 0) such that its Z axis, i.e.,  $Z_1$  lies along the axis of joint 1. The origin of this frame should be at the bottom of the base link. The direction of the  $X_1$  axis can be chosen arbitrarily. However, setting it as the direction of robot's X axis (as per the installation of robot on its foundation) is preferred as it will be easy to correlate the coordinates shown in the robot's teach pendant and those obtained in a virtual software.  $Y_1$  axis is obtained as a cross product of  $Z_1$  and  $X_1$ . Hence, the coordinate frame is determined completely.
2. To attach a DH frame  $i+1$  on each subsequent link ( $i=2, \dots, 6$ ), its Z axis, i.e.  $Z_i$ , is aligned along the axis of the joint  $i$  and  $X_i$  is aligned along the common normal between the axes of joints  $i-1$  and  $i$ ,  $Z_{i-1}$  and  $Z_i$ , respectively.  $Y_i$  is determined as the vector cross-product of  $Z_i$  and  $X_i$ . The origin of the DH frame,  $O_i$ , is located at the intersection of  $X_i$  and  $Z_i$ .
3. To attach a DH frame on the last link, i.e., the end-effector (EE),  $Z_7$  is aligned parallel to  $Z_6$  and frame origin  $O_7$  is located at the tip of the end-effector, where  $X_7$  is considered the common normal between  $Z_6$  and  $Z_7$ .
4. Identify and measure the six sets of DH parameters between the base link (Link 0) and Link 1 on the physical robot. Similarly, for all the subsequent consecutive links till the end-effector (Link 7).

5. Alternatively, one can also use the specification sheet of the robot given by the robot manufacturer, to find the required parameters, as given in Figure 3.

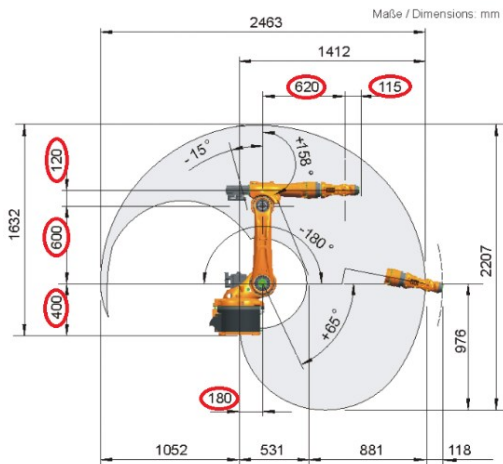
The DH parameters measured from a physical robot, KUKA KR5 arc, are reported in Table 2, where JV stands for Joint Variable. It was verified that the values match with those circled in a diagram for the robot's specification sheet, shown in Figure 3.

**Table 2: Measured DH parameters of KUKA KR5 Arc robot**

Joint	Joint Offset ( $b$ in m)	Joint Angle ( $\theta$ in $^\circ$ )	Link Length ( $a$ in m)	Twist Angle ( $\alpha$ in $^\circ$ )
1	0.4	0 (JV)	0.18	90
2	0	90 (JV)	0.6	180
3	0	0 (JV)	0.12	-90
4	0.62	0 (JV)	0	90
5	0	0 (JV)	0	-90
6	0.115	0 (JV)	0	0



**Figure 2: DH frames for KUKA KR5 Arc robot**



**Figure 3: Dimensions in KUKA KR5 Arc specifications [7]**

## 2.2 Robot model in RoboAnalyzer

Once the DH parameters of a physical robot are measured, a skeleton model of the virtual robot can be easily created in RoboAnalyzer software. The simple user interface allows even a novice computer user to enter the DH parameters and 3D model is rendered instantly. A screenshot of the skeleton model of the KUKA KR5 Arc robot is shown in Figure 4.

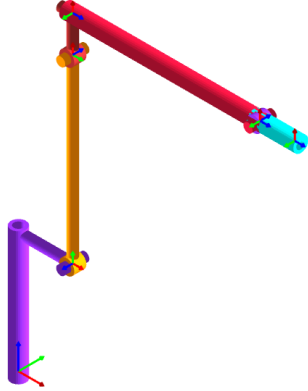


Figure 4: Skeleton model of KUKA KR5 Arc in RoboAnalyzer

## 2.3 Visualization of DH parameters

As mentioned earlier, the understanding of DH parameters is very crucial to further understand robot kinematics, namely, forward and inverse kinematics. Once the skeleton model of the given robot is developed in RoboAnalyzer by a robot technician, each DH parameter can be visualized very easily. Upon selection of a joint and any of the four parameters, a coordinate frame moves in the 3D model, representing the parameter. An example coordinate frame movements for 'Joint Offset' and 'Twist Angle' for Joint 1 are shown in Figure 5 (a) and (b), respectively. Also, the four DH parameters between two DH frames can be visualized with motion of four coordinate frames in succession. The animations between various DH frames helps the technician to understand the effect of various DH parameters.

Using the four DH parameters, a Homogenous Transformation Matrix (HTM) can be used to represent the relative position and orientation of DH frame ( $i + 1$ ) with respect to DH frame  $i$  using

$$T_i = \begin{bmatrix} \cos \theta_i & -\cos \alpha_i \sin \theta_i & \sin \alpha_i \sin \theta_i & a_i \cos \theta_i \\ \sin \theta_i & \cos \alpha_i \cos \theta_i & -\sin \alpha_i \cos \theta_i & a_i \sin \theta_i \\ 0 & \sin \alpha_i & \cos \alpha_i & b_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

More details about DH parameters can be found in [6]. Models of various industrial robots with their CAD models are available in the software which could be used to get a better understanding of relation between DH parameters and physical properties of the robot.

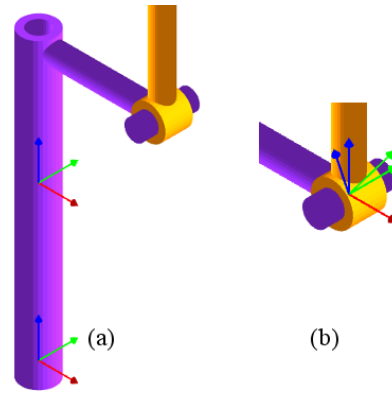


Figure 5: Visualization of DH parameters. (a) Animation of Joint Offset as Translation (b) Animation of Twist Angle as Rotation

## 3. FORWARD KINEMATICS

A robot technician uses a combination of joint-jogging and Cartesian-jogging to teach a robot different positions using the teach pendant of the robot. The technician should also understand that a robot typically performs tasks in Cartesian space but the robot joints are controlled in joint-space. Hence, the correlation between the two spaces is of prime importance.

For a given robot with known DH parameters, which include the joint angles, the method of finding the pose or the configuration of the end-effector (EE) is known as forward kinematics. To find the pose of the EE for a 6-axis serial robot, the individual HTMs between DH frames from base link (frame 1) to the EE link (frame 7) should be multiplied in the same order as below:

$$T = T_1 T_2 T_3 \dots T_6 \quad (2)$$

which can further be represented as

$$T = \begin{bmatrix} Q_{3 \times 3} & A_{3 \times 1} \\ 0 & 1 \end{bmatrix} \quad (3)$$

where,  $Q_{3 \times 3}$  represents the orientation of the end-effector (frame 7) using direction cosine methodology and  $A_{3 \times 1}$  represent its position vector with respect to frame 1. In forward kinematics, the right hand side of (2) is completely known and left hand side is calculated as output.

If a robot technician has to understand the HTM between frame 7 and frame 1, RoboAnalyzer displays the HTM along with two coordinate frames for frames 1 and 7. Thus, helping the technician to understand both mathematically and graphically. An example EE pose is given in Figure 6. The technician can also give the same joint angles, as given in RoboAnalyzer, to the physical robot. The EE pose values, typically shown in a teach pendant, can be observed and compared with the values obtained in RoboAnalyzer. This would also help in effective understanding.

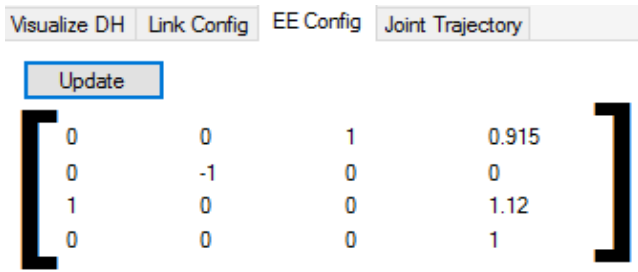


Figure 6: HTM for the end-effector in RoboAnalyzer

### 3.1 Visualization of Robot Motion

Visualization of robot path in 3D is difficult with only the kinematic equations of the robot. Here, robot visualization software play an important role by helping in visualization of the robot path in the 3D space along with the trace path of the EE during the motion. RoboAnalyzer allows the user to simulate motions of any serial robot using its DH parameter as an input along with the joint motions. It also displays the HTM of EE for current robot configuration. An image of skeleton model of KUKA KR5 Arc robot is given in Figure 7.

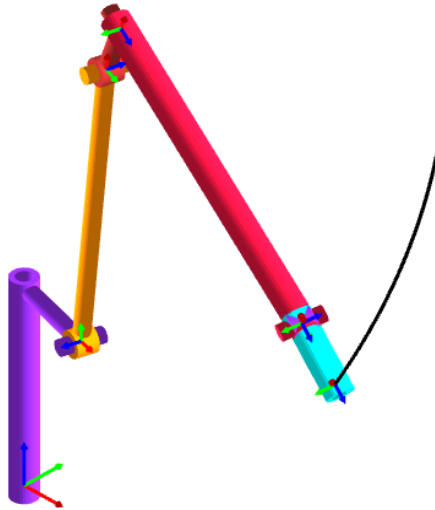


Figure 7: Simulation of robot motion and trace of EE path in RoboAnalyzer

RoboAnalyzer also provides a Virtual Robot Module (VRM) which allows a user to control one of the preloaded industrial robots using a teach pendant type interface. This can find good usage in the training of robot technicians before giving them a real robot. It allows the operator to observe the motion in both joint motion control and Cartesian control of the robot, as illustrated in Figure 8.

The authors have plans to include static obstacles, workcell and other items in the workspace of the robot to provide realistic understanding of the robot motion in a workcell.

## 4. INVERSE KINEMATICS

Inverse kinematics refers to the problem of finding the possible joint values (Joint Angles for revolute joints and Joint Offsets for prismatic joints) when the pose of the end-effector is known. So, in inverse kinematics, the left hand side of (2) is known but the right side is known. Unlike forward kinematics problem which has a

unique solution, inverse kinematics of serial manipulators may have multiple solutions. More details can be found in [8].

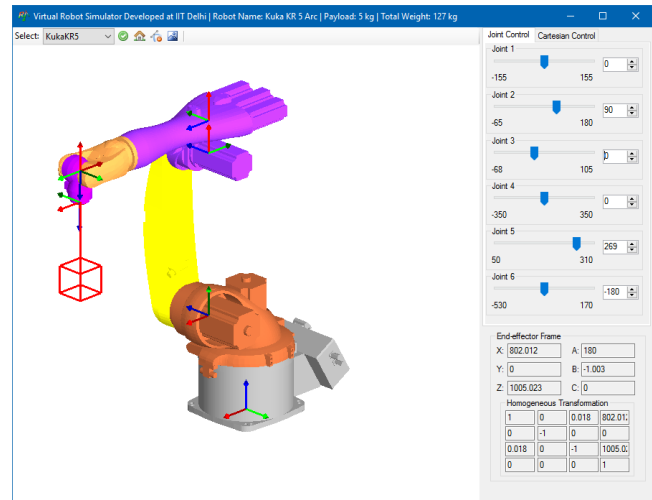


Figure 8: Virtual Robot Module (VRM) in RoboAnalyzer

Finding the solutions to this problem is a difficult task in which software like RoboAnalyzer can play an important role. RoboAnalyzer provides a robot technician with an Inverse Kinematics module in which the DH parameters of most industrial robots can be used as input to find all possible solutions of the robot's joint values. An example inverse kinematics analysis is shown in Figure 9.

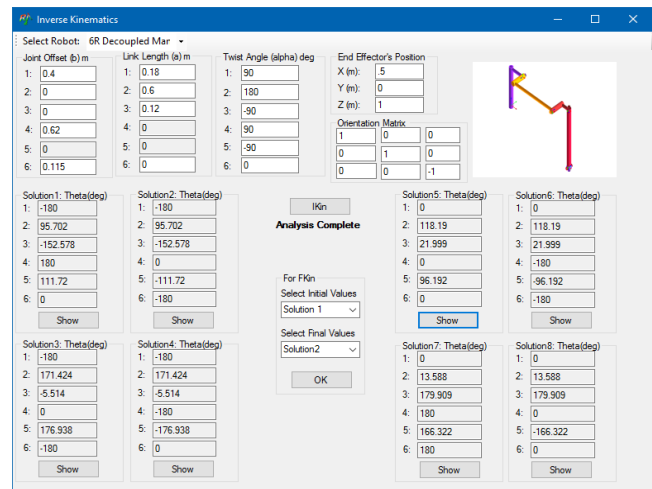


Figure 9: Inverse Kinematics analysis showing all possible solutions for KUKA KR5 Arc robot

Apart from displaying the joint values, it also updates the 3D robot model for a selected solution set. Later, using the Forward Kinematics analysis in the software, the technicians can further compare the HTM of the EE with the input given in the Inverse Kinematics analysis. Thus, it helps in improving the understanding of kinematics. It further provides an option to view animation of robot motion between two possible solutions set, which may further improve the understanding of existence of multiple inverse kinematics solutions.

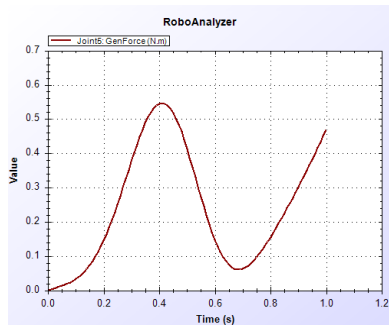
## 5. INVERSE DYNAMICS

Inverse dynamics refers to the problem of finding the forces on the joints due to gravity acting on the robot and the prescribed robot motion. To solve inverse dynamics problem, center of mass and moment of inertia of individual links are also required along with the DH parameters of the robot. Though the analysis is useful for selecting motors/actuators while modeling and design of robot, the robot technicians should have some idea about the forces that act on a robot while it is operating.

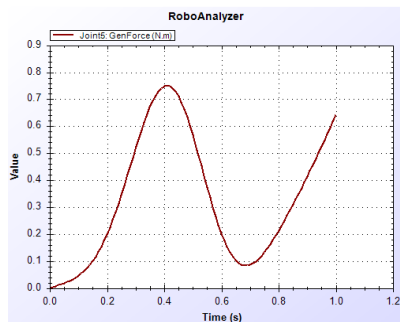
For instance, if a robot link is obstructed by some object during the motion, the current in the robot actuators would increase considerably above the rated current in them, which could damage the motor drives and motors. Another example is that of a robot's load at the EE (gripper) being more than the payload capacity of the robot. In which case, the robot might have incorrect motion. Technicians could use RoboAnalyzer to understand that for higher payload at the EE link, higher torques are required in some of the robot actuators.

An illustration of torque required for Joint 5 of KUKA KR5 Arc robot for a prescribed motion for lower mass ( $m = 0.016$  kg) is given in Figure 10(a) and for higher mass ( $m = 0.2$ kg) is given in Figure 10(b). By comparing both the plots produced by RoboAnalyzer, one can understand that the torque requirement increases with increase in payload.

Using the fact that current drawn by a motor is directly proportional to the torque delivered by it at a constant speed, change in energy consumption by the robot under varying payload conditions could be easily estimated.



(a) Input torque for Joint 5 for lower mass of EE link



(b) Input torque for Joint 5 for higher mass of EE link

**Figure 10: Motor torques calculated for Joint 5 for different mass of EE link**

## 6. CONCLUSIONS

RoboAnalyzer is a visualization and educational software which has been developed to create a better understanding of robotics. In this paper, an overview of how RoboAnalyzer software can be used to improve the knowledge and skills of robot technicians was given. The method for measuring DH parameters of a physical robot was explained and its modeling in RoboAnalyzer is discussed. Further, how RoboAnalyzer can be used to understand the DH parameters, forward and inverse kinematics was explained. Inverse dynamic analysis can improve the understanding of the torque requirements at joints for prescribed motion under various payload. Robot technicians can also explore the forward dynamic analysis in RoboAnalyzer software to understand how forces acting on the robot can cause the motion. In summary, RoboAnalyzer would help robot technicians to understand the mechanics of robots and thus making them more productive.

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