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An Effective Way of Teaching Fundamentals of Robotics to Undergraduate Students using RoboAnalyzer

Amit L Talli[1], Vinod Kumar V Meti[2], Arunkumar C Giriyapur[3]
amit@kletech.ac.in, vinod_meti@kletech.ac.in, aaron@kletech.ac.in
KLE Technological University, Vidyanagar, Hubli – 580031.

Abstract: Robots are becoming increasingly important as the world continues to evolve. Robots are needed to achieve higher production rates and competitiveness. Many universities have already started to offer robotics courses in response to the growing demand for automation. However, in a traditional classroom teaching method, students find it challenging to apply pure mathematical algorithms in robotics. The lack of visualization of robot modelling affects the students learning interest. It becomes imperative to introduce simulation software in teaching the fundamental concepts of robotics. This paper presents the application of the RoboAnalyzer tool to teach the robotics course at the undergraduate level. The methodology was adopted to complement the theoretical concepts of robotics. In the present study, we collected feedback from the students about the method. The results show that around 76 % strongly agreed that the RoboAnalyzer tool improved learning efficiency, and 74 % strongly agreed that the combination of conventional teaching and the simulation tool is better than the traditional teaching method. RoboAnalyzer was implemented during the academic year 2019 – 2020 and received a positive response.

Amit L Talli
amit@kletech.ac.in

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1. Introduction

The robotics field is generating considerable interest due to the wide variety of applications in health care, manufacturing industries, space, mining, defense, agriculture, etc. Experts have always seen robotics as the leading technology of the fourth industrial revolution. By 2026, the robotics market will reach 74.1 billion US dollars . Robotics courses and minor degree programs are now being offered by universities, engineering, and technical colleges. Robot kinematic model is one of the core topics of serial chain robotics. This includes forward and inverse kinematics, jacobian, singularity analysis, trajectory planning, path planning, etc. These topics are important and required to apply theoretical knowledge to real-world problems of industrial robots. The other part, known as dynamics, deals with the torque or force control. Mathematical knowledge such as linear algebra, calculus, geometry, and mechanics is required to understand the fundamentals of robotics. However, robot technology is very complex. Robot architecture, motion, etc., are difficult to grasp without hands-on experience with real industrial robots or any supporting tool. For example, Arnay (2017) reported the difficulties faced by the students due to mathematical or geometrical knowledge required to understand the concepts of robotics –.

The issues faced by the teachers and students while teaching and learning robotics compelled researchers to develop an application or toolbox to tackle the hurdle. In the literature, many software packages and toolboxes have been developed to complement concepts of robotics in the past " . Arnay (2017) compared several robot simulation programs developed specifically for the robotics – . Das (1999) developed a software package known as Robot Computer-Aided Analysis and Design (RCAAD) for planetary landers, flight research, and rovers . Similarly, Hill and Tesar (1996) developed a standalone command line-based tool known as Rapid Analysis Manipulator Program (RAMP) to analyze serial robots . However, these software tools were not intended for educational purposes – . Several toolboxes have been developed based on proprietary software such as MATLAB or Mathematica. ARTE, Robotics Toolbox by Peter Corke, Robotica etc., are some of the toolboxes developed for educational purposes. However, these toolboxes require proprietary software packages to work. Some colleges may not have access to such proprietary software packages. Othayoth (2017) reported several PC-based software packages tools such as Robotect, CoppeliaSim, RoKiSim, RoboDK, Webots, etc., (Othayoth et al., 2017). These software's are intended

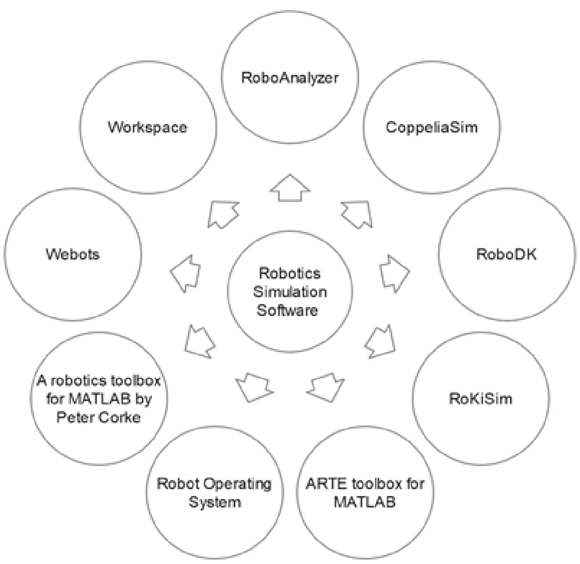

Fig. 1: Robot simulation software

for analysis, simulation incorporated with virtual sensors and actuators, and programming. Some software packages are capable of simulation of mobile robots with the virtual environment, such as CoppeliaSim. Sabnis (2021) reported modelling and simulation of an industrial robot using computer-aided design software (Sabnis et al., 2021). However, this method is time-consuming and requires good knowledge of computer-aided skills (A. L. Talli et al., 2020). RoboAnalyzer is another evolving software tool developed at IIT Delhi for educators, students, and researchers (Gupta et al., 2017; Othayoth et al., 2017). Fig. 1 presents the canvas of software packages and toolboxes developed for robotics. The present landscape is populated with a variety of software packages and toolboxes to fulfill the needs. The present situation demands a simulation tool to build a strong relationship between the students and fundamental concepts of robotics. Gupta (2017) states that the comprehension of robot motion is further enhanced by implementing a visualization tool (Gupta et al., 2017).

The present paper examines the effectiveness of t eaching fundamentals of robotics using RoboAnalyzer. Our work aims to train and develop the skills of students in the robotics field. We chose this particular approach to complement the theoretical concepts and motivate the students through simulations. The software is implemented to help the undergraduate students to build robot models based on Denavit – Hartenberg (DH) parameters. Furthermore, the students are trained to solve the forward and inverse kinematics problems, visualize the joint movement, etc. Finally, the effectiveness of this approach is collected from the feedback questionnaire or survey. The majority of respondents felt positive and interested to learn robotics concepts.

This paper is divided into five sections. Section 2 provides an overview of the methodology. Section-3 introduces the RoboAnalyzer with few examples. Section-4 describes the evaluation and student feedback. Section 5 presents the conclusion of the paper.

2. Methodology

In the present section, the contents of the robotics course are shown in Table 1. The course duration and credits for the undergraduate program were decided at the university level.

Table 1: Course contents

Chapter No.	Title	Hours
1	Introduction to Robotics and Applications	2
2	Representing Position and Orientation	4
3	Position Analysis of Serial Manipulators	8
4	Jacobian Analysis of Serial Manipulators	6
5	Statics and Dynamics of Serial Manipulators	6
6	Trajectory planning	7
7	Wrist Mechanisms	7
8	Tendon-Driven Manipulators	5
9	Robot End-Effectors	5

The four-credit (4-hours per week) was offered to second-year or fourth-semester undergraduate students. The lesson plan containing the course contents was distributed to the students before the commencement of the semester. Every course content in the lesson plan is equipped with course outcomes (Cos). The course outcomes (COs) of the robotics course are as follows:

1. Explain the design and construction of robots, as well as their wide application (L2)

2. Locate an object's position and orientation in 2-D and 2-D Cartesian space analytically using vectors and matrices (L2)

3. Develop the Homogeneous transformation matrix by using Denavit–Hartenberg parameters for serial manipulators (L3)

4. Generate a trajectory planning for smooth robot motion by using polynomials. (L3)

5. Describe the working principle of the wrist mechanism and draw the kinematic diagram of the wrist mechanism(L2)

6. Perform Kinematic & Static analysis of Tendon – Driven mechanism (L3)

3. Design and select robot end-effector to perform a specific task (L3)

Each course outcome is assigned with the knowledge level as per Bloom's taxonomy level, e.g., L1 - Knowledge, L2 - Understand, and L3 - Apply. Furthermore, the course outcomes (COs) are mapped with the program outcomes (POs).

The program outcomes (POs) of a specific program or department are aligned with the graduate attributes (GAs) recommended by the National Board of Accreditation (NBA). Fig. 2 shows the graduate attributes (GAs).

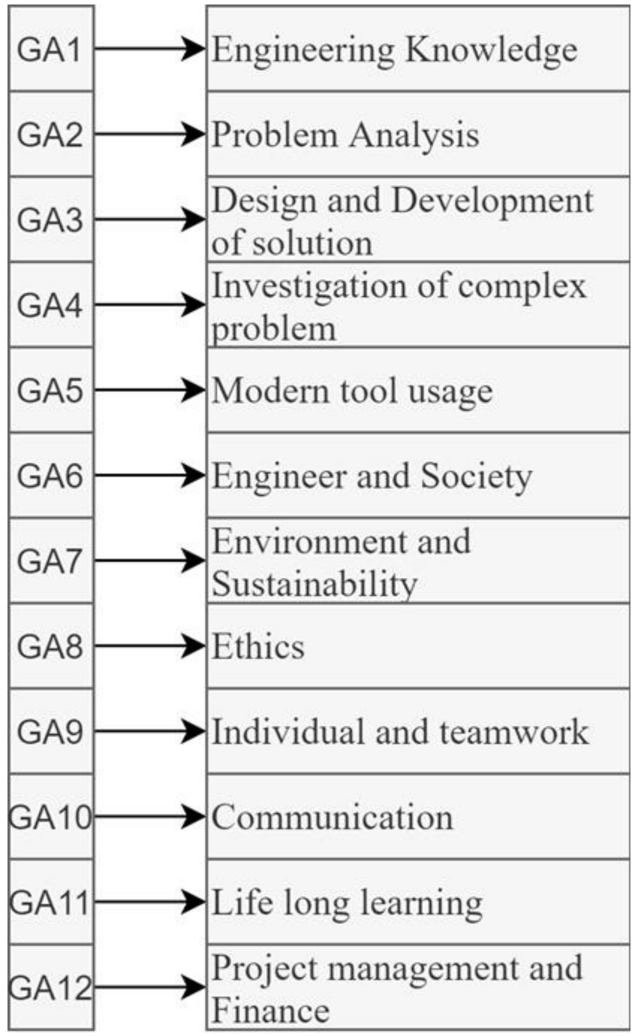

Fig. 2.: Graduate Attributes (GAs)

NBA has established specific parameters known as Graduate Attributes (GAs) for the engineering programs. Outcome-Based Education (OBE) enables transformation in curriculum, new practices in education to enhance learning and engineering graduate skills. This brings a positive attitude in teaching and assessment methods in academics (Bhagyalakshmi et al., 2015). The respective departments align their program outcomes (POs) with the graduate attributes (GAs). Furthermore, the applicable program outcomes (POs) are then mapped with the course outcomes (COs). The GA-PO-CO mapping is shown in Fig. 3.

Table 2 : Course Outcomes - Program Outcomes Mapping

COs\POs	a	b	c	d	e	f	g	h	i	j	k	l
1	M											
2	M	H										
3	M	H	M		H						M	
4	M	H	M		H						M	
5	M											
6	M	M										
7	M	M										

Where, L: Low, M: Medium, H: High

Table 2 presents the course articulation matrix: Mapping of Course Outcomes (CO's) with Program Outcomes (Pos).

Several authors have highlighted the problems faced by the students while studying the concepts of robotics, such as kinematics, transformation, geometry, and perception of robot motion (Arnay, Andez-aceituno, et al., 2017; Othayoth et al., 2017; Zhou et al., 2020). We selected some contents such as robot modelling, transformations, forward and inverse kinematics, etc., which require mathematical and geometrical skills at the initial stage. These contents were used to teach along with the RoboAnalyzer. The RoboAnalyzer was selected due to its standalone features, minimal resources, and visualization. It can be downloaded directly from the website, http://www.roboanalyzer.com/.

A. Forward and Inverse Kinematics

Forward and inverse kinematics are the two important concepts dealt with in serial chain robotics. The position of an end-effector for the specified joint values is determined by forward kinematics. Conversely, inverse kinematics determines the joint values for the specified position of an end-effector (A. Talli & Marebal, 2021b).

1) Forward Kinematics

Denavit – Hartenberg (D-H) method is used in robot kinematics (Ha, 2008). The D-H method uses screw theory to show the transformation of coordinate frames (Denavit & Hartenberg, 1955). The D – H method is the de-facto standard for describing the robot's entire architecture (A. Talli & Marebal, 2021a). The students must read and understand the D-H parameters of various robots. Table 3 shows the D-H parameters.

Students were encouraged to draw a rough sketch

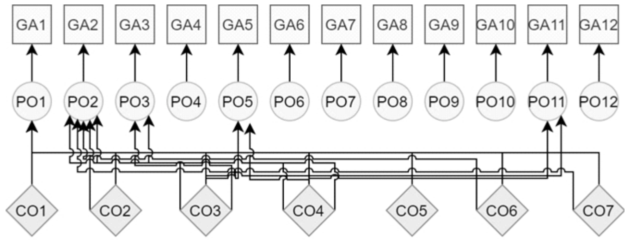

Fig. 3 : GA-PO-CO Mapping

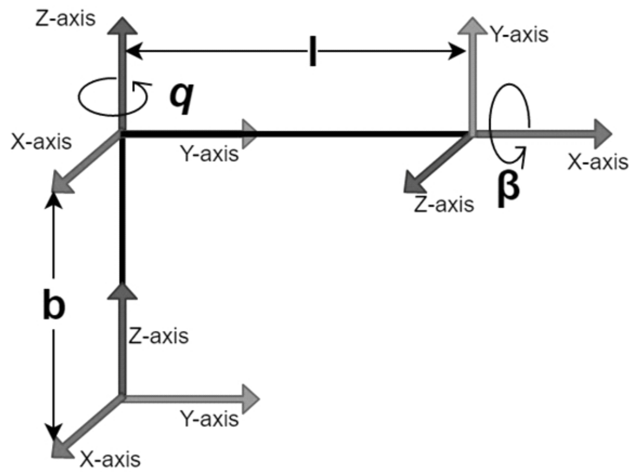

Fig. 4 : Denavit-Harternberg parameters

Table 3. d-h parameters

Parameters	Symbol	Description
Link Offset	b	The displacement along the z-axis
Joint Angle	q	The angular displacement about the z-axis
Length of link	l	The displacement along the x-axis
Twist Angle	β	The angular displacement about the x-axis

of a robot from D-H parameters to attach coordinate frames is shown in Fig. 4. Table 3 shows the four parameters for describing the robot structure. The joint parameters are considered variables, and link parameters are considered constants. The joint type could be revolute or prismatic, depending upon the robot's configuration. The other two parameters define the link length and twist angle.

The robot kinematics involves the multiplication of 4 X 4-dimensional matrices. The resultant general transformation matrix is obtained from Table 3. Equation (1) represents the 4 X 4 transformation matrix is as follows:

$$T=\begin{bmatrix} cos(q) & -sin(q)cos(\beta) & sin(q)cos(\beta) & acos(q) \\ sin(q) & cos(q)cos(\beta) & -cos(q)cos(\beta) & asin(q) \\ 0 & sin(\beta) & cos(\beta) & b \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Equation (1) is also referred to as a homogeneous transformation matrix. The mathematical complexity of transformation increases as the mobility or degrees of freedom increases. As reported earlier, mathematical and geometrical operations are troublesome for the students. Furthermore, the difficulty level also increases as the robot configuration becomes complicated. For six degrees of freedom robot manipulator, the pose of the end-effector is determined by the following equation:

$$^{Base}T_{End\text{-}effector} = {}^0T_1 * {}^1T_2 * {}^2T_3 * {}^3T_4 * {}^4T_5 * {}^5T_6 \quad (2)$$

Base TEnd-effector, shows the pose of end-effector with respect to the foundation or base. For the sake of simplicity, the Eqn. (2) is written in compact form. The chain of transformation matrix yields a four-dimensional transformation matrix consisting of rotational and positional elements.

2) Inverse Kinematics

Inverse kinematics is used to obtain the joint values for the specified position (Kucuk & Bingul, 2010). The inverse of transformation yields multiple

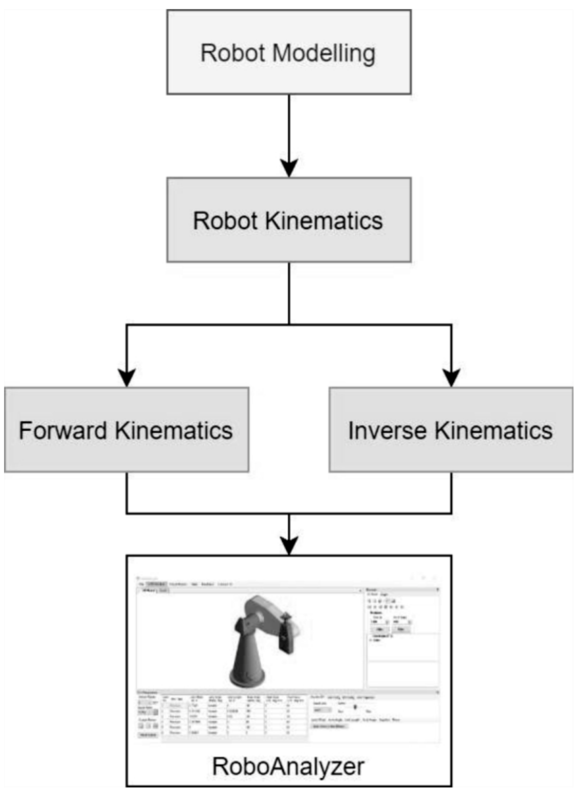

Fig. 5 : Process of robot kinematics using RoboAnalyzer

solutions to a specific position. Inverse kinematics is complicated as compared to forward kinematics (Sadanand et al., 2016). It consists of non – linear equations, and it becomes difficult for the students to solve and perceive simultaneously. The steps followed in inverse kinematics are shown in the following equations. Equation (1) is rewritten to obtain the following equation:

$$[{}^0T_1]^{-1} * {}^{Base}T_{End\text{-}effector} = [{}^0T_1]^{-1} * {}^0T_1 * {}^1T_2 * {}^2T_3 * {}^3T_4 * {}^4T_5 * {}^5T_6 \quad (3)$$

Where $[{}^0T_1]^{-1} * {}^0T_1 = I$ (Identity matrix) and the Eq.(3) is written in simplified form:

$$[{}^0T_1]^{-1} * {}^{Base}T_{End\text{-}effector} = {}^1T_2 * {}^2T_3 * {}^3T_4 * {}^4T_5 * {}^5T_6 \quad (4)$$

Eqn. (4) is further simplified to yield the value of the first joint.

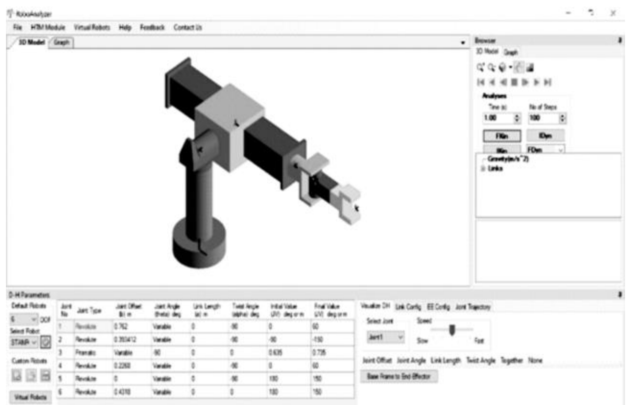

Fig. 4 : RoboAnalyzer interface

Similarly, the other values can be obtained by inverting the equations.

3. Roboanalyzer

This section discusses the process of robot modelling using RoboAnalyzer. Fig. 5 presents the

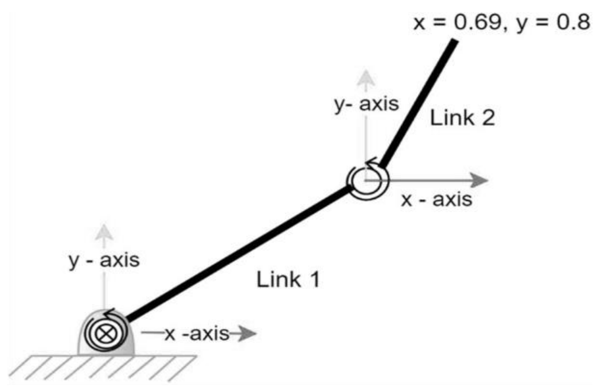

Fig. 6: Line diagram of 2- DoF planar robot

process followed for the robot modelling. As stated in the methodology, the two approaches involved in robot kinematics are forward and inverse kinematics. Teaching and learning the robot kinematics solely based on textbooks is quite challenging due to limited access to the actual or real industrial robots. It is challenging to visualize the concepts of robotics without any aid of software tool (Sadanand et al., 2016).

In the first step of the process, the robot models are built based on DH parameters in RoboAnalyzer. Then, the initial and final joint values are specified to simulate a robot. After these steps have been carried out, forward and inverse kinematics results are obtained. Furthermore, the results obtained from the analytical derivations are verified using the Robo Analyzer for validation. This method complements the course and motivates the students.

A. A Few Examples

The present section provides a step-by-step solution of a set of examples using RoboAnalyzer. Initially, the students are asked to draw a line diagram of a simple two degrees of freedom (DoF) planar robot from D-H parameters, as shown in Table 4.

Table 4 : d-h parameters of 2-dof planar robot

Link	q	b	l	.
1	q_1	0	0.8	0
2	q_2	0	0.4	0

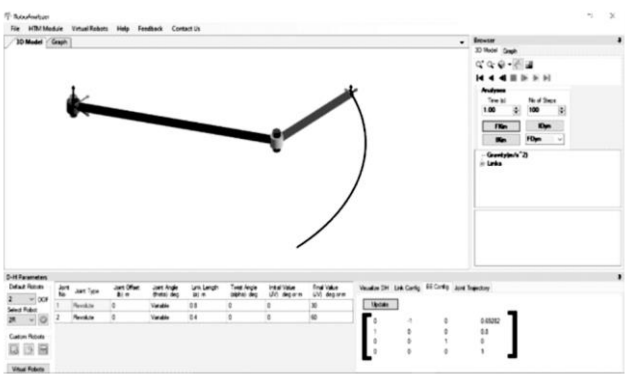

Fig. 7 : Modelling of 2- DoF planar robot in RoboAnalyzer

As shown in Table 4, four parameters are used as Joint variable (q), Link offset (b), link length (l), and Twist angle (β). The unit for joint variable and twist angle is described in 'degree or radians', and link offset and link length is described in 'meter'. The line diagram of the two – degrees of freedom (DoF) planar robot is shown in Fig. 6.

After drawing the line diagram of the planar robot, the students are guided towards developing kinematic equations analytically. The forward kinematic equations are developed by using the D-H parameters. Kinematic equations are derived using the chain of the homogeneous transformation matrix (A. Talli & Giriyapur, 2021).

Base TEnd-effector = Trans(q1) * Trans(b1) * Trans(l1) * Trans(β1) * Trans(q2) * Trans(b2) * Trans(l2) * Trans(β2) (5)

Equation (5) represents the compact format of the 4 X 4 homogeneous transformation equation, and the subscript represents the parameters associated with the link number, simplification of Eqn. (5) yields Eqn. (6) and (7)

$$X = 0.4\,C12 + 0.8\,C1 \quad (6)$$

$$Y = 0.4\,S12 + 0.8\,S1 \quad (7)$$

Equation (6) and (7) represents the position of two – degrees of freedom planar robot. For the sake of simplicity, Cos (q1 + q2) = C12 and Sin (q1 + q2) = S12.

The developed forward kinematic equations are validated using RoboAnalyzer. By substituting joint variables, q1 = 30o and q2 = 60o in Eqn. (6) and (7) yields:

X = 0.692 m and Y = 0.8 m

After obtaining the analytical results, the students are asked to build the same model in RoboAnalyzer.

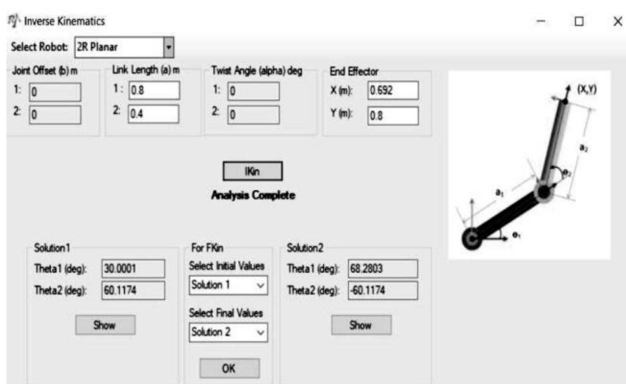

Fig. 10: Inverse kinematics of 2 – DoF planar robot

Fig. 7 shows the 2- DoF planar robot built using RoboAnalyzer.The position values of the 2- DoF planar robot for specified joint values in RoboAnalyzer are shown in Fig. 8.

The position values for the specified joint values are then compared with the analytically obtained values for consistency.

Similarly, the inverse kinematic equations are derived for the two links planar robot, and the joint values are determined for the known configuration of the robot. The inverse kinematics is activated by clicking the "IKin" option, as shown in Fig. 9.

The inverse kinematic equations are obtained by adding and squaring Eqn (6) and (7). Inverse kinematics is not easy compared to forward kinematics due to highly non-linear trigonometric functions (Othayoth et al., 2017). The developed inverse kinematic equations are cross-checked with the same position values analytically. Furthermore, the equations are also validated using the inverse kinematic module of RoboAnalyzer. The 2- link planar robot is selected from the dropdown menu to specify link length position in the X and Y direction, shown in Fig. 10. The RoboAnalyzer also performs inverse kinematic analysis for six degrees of freedom robot manipulator. The inverse kinematics yields up to eight solutions for the robot's specific configuration. Similarly, more complex problems can be visualized by using RoboAnalyzer. The robots such as 2R, 2P, RP, PR,3R, RRP,3R Articulated, Wrist, PPPRR, MTAB Mini, 6R Decoupled Manipulator, Kuka KR5 Arc, MTAB Aristo, SmallArm, and 6R Generic Manipulator are available for the inverse kinematics.

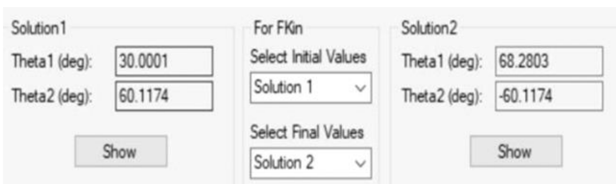

Fig. 11:Possible solutions of inverse kinematics of 2 –DoF planar robot

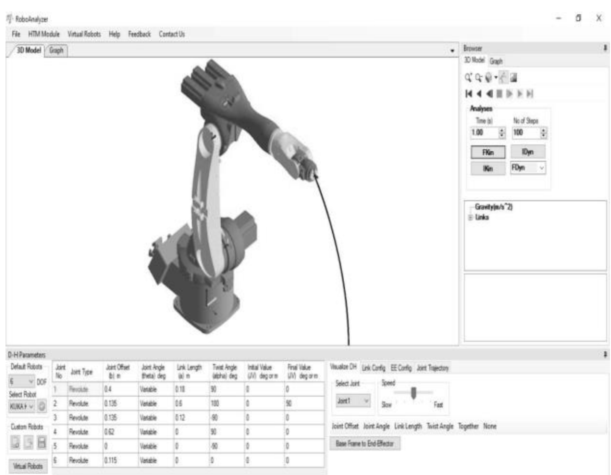

Fig.12 : Kuka KR5 Arc robot (6 – DoF) in RoboAnalyzer

Fig. 11 shows the two possible solutions for the inverse kinematics.

B. Virtual Robot Module

This section presents the other features and examples of RobAnalyzer used for teaching robotics. Fig. 12 shows the RoboAnalyzer interface with six-

Table 5 : robot models in roboanalyzer

Degrees of Freedom	Robot Model
1	1P and 1R
[illegible]	[illegible]

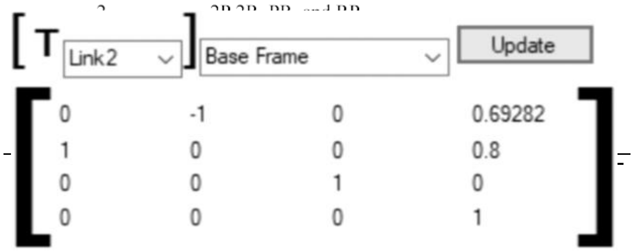

Fig. 8. Position values in RoboAnalyzer

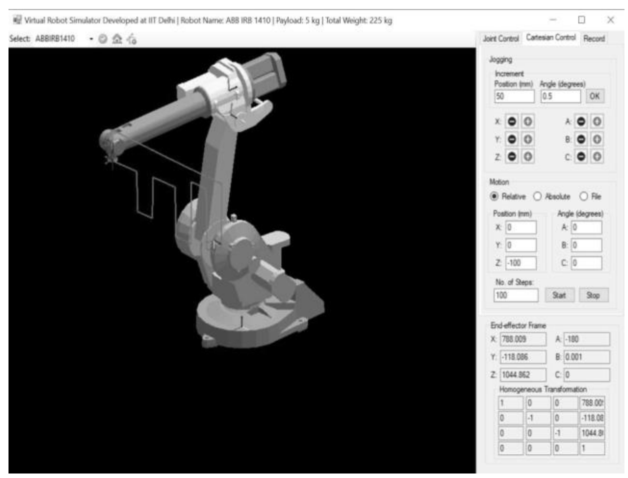

Fig. 9: Analyses option in RoboAnalyzer

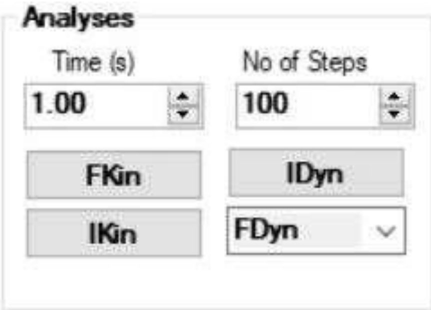

Fig. 9: Analyses option in RoboAnalyzer

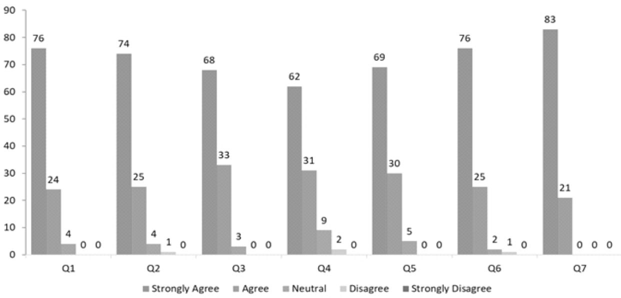

Fig. 14 : Student feedback

degrees of freedom industrial robots performing simulation—other robots such as KUKA KR5 Arc, PUMA, STANFORD, ARISTO, etc., are available to explore. Furthermore, the robots are also classified under degrees of freedom in RoboAnalyzer is shown in Table 5.

The RoboAnalyzer also comes with the Virtual Robot Module (VRM), enabling students to visualize joint and cartesian control. In the joint control tab, a user can jog the joints within the specified range, and the position of the end-effector instantly updates the contents of the transformation matrix (Othayoth et al., 2017). The users can also trace the end-effector path in RoboAnalyzer, which helps to correlate the path traveled as per the joint motion. Under Cartesian control, the students can draw the welding profile using a virtual robot from the available robot model available from the dropdown menu. The jogging control consists of jogging in x,y, and z-direction and angle in A, B, and C for controlling rotational motion. The jogging can be controlled incremental fashion with a smaller resolution. Fig. 13 shows the path performed by using the cartesian control tab. The path can be exported to an excel sheet that contains the data regarding the path. The students could generate different paths, such as welding paths, and record the path as well.

4. Evaluation And Student Feedback

The present section discusses the reaction of undergraduate students. To conclude the robotics course, the students were asked to select an industrial robot to perform the kinematic analysis for the course project. The students were asked to acquire the D-H parameters of the selected robot from the manufacturer catalog or through references. The students should build the robot model in RoboAnalyzer based on D-H parameters. The students should enter all the D-H parameters in the RoboAnalyzer for forward and inverse kinematic analysis.

This type of exercise/project trains them to visualize the D-H parameters and joint motion. Furthermore, students were asked to prepare a report on the robot modelling performed using the RoboAnalyzer.

In order to validate the proposed method, opinion surveys were conducted with undergraduate students. The opinion surveys were conducted using an electronic form such as Google forms. The electronic form consisted of seven statements are shown in Table 6. The electronic form was based on a five-point Likert scale satisfaction questionnaire (A Technique for the Measurement of Attitudes. - PsycNET, n.d.). This method was used to evaluate the presented application of RoboAnalyzer and improve if needed for the next semester. Table 6 presents the statements or questions, along with the five-point Likert scale statements (point-1 stands for strongly disagree, point-2 stands for disagree, point – 3 stands for neutral, point – 4 stands for agree, and point-5 stands for 5-strongly agree) (A Technique for the Measurement of Attitudes. - PsycNET, n.d.). Fig. 14 presents the feedback survey results undertaken to analyze the teaching method implemented for the robotics course. The feedback questionnaire was sent to 104 students undergone the course.

Table 6 : Statements sent to undergraduate students

No.	Questions/Statements
1	The application of the RoboAnalyzer simulation tool improves learning efficiency.
2	Combining theoretical concepts with simulation tools complements the robotics course.
3	I can interpret Denavit - Hartenberg parameters.
4	Solving inverse kinematics is easier.
5	The teaching method has strengthened my knowledge regarding robot kinematics.
6	The same approach can be used in other areas of the robotics course.
7	I am interested in robotics.

The replies for statement 1 (Table 6 and Fig. 14) indicated that the application of the RoboAnalyzer tool received a positive response, with ratings of 4 or 5 given in 96.15 % of the replies, on average. Statements 2 and 3 (Table 6) concern the view of the students to the implementation of a simulation tool in learning theoretical concepts and comprehension of robot kinematics, such as building a robot using Denavit- Hartenberg parameters. In this case, ratings of 4 or 5 were obtained in 95 % of the replies, on average. Statement 5 and 6 received ratings of 4 or 5 were given in 95.1 % and 97.1 % of the replies, on average. In response to statement 7 (Table 6 and Fig. 14), nearly 83% of the responses strongly agreed that they are interested in robotics. However, a slightly lesser agreement regarding statement 4 was noticed regarding the inverse kinematics. In this case, ratings of 5 were given only 68 % of the responses, respectively. The authors would like to consider this viewpoint and improve the method towards inverse kinematics.

5. Conclusion

This article describes a method adopted for teaching robot kinematics to undergraduate students. The feedback survey conducted with undergraduate students of the 2019 – 2020 academic year was encouraging and provided helpful information related to the methodology. The methodology consisted of delivering fundamentals of robot kinematics using RoboAnalyzer. This method was adopted to increase the interest, ease of visualization of the theoretical concept. The students are also encouraged and motivated to learn robotics using different software tools. The present work has only implemented the RoboAnalyzer tool for the robot kinematics portion at present. The methodology's effectiveness was measured based on a feedback questionnaire. The results reflect the feelings of students about the robot kinematics along with the RoboAnalyzer tool. We have found that the students accepted the implementation of RoboAnalyzer tool in learning fundamental concepts of robots. However, the results also show that inverse kinematics remains a challenging concept to understand. Furthermore, students also agreed to implement such simulation tools in other areas of robotics. The authors will use the feedback to explore new teaching approaches and tools in robotics.

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