VIRTUAL REALITY: A TOOL FOR LEARNING ROBOTICS

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Abstract. In robotics courses are used kinematics and dynamics equations to resolve almost all standard problems and their solutions are presented by schematics, diagrams or tables. Robotics researchers and students put down big effort to interpret the algorithms outputs or to imagine the robot movements from Cartesian graphics of positions, velocities and accelerations. Computer applications with Graphics User Interfaces (GUI) show the robot movements with links represented by straight lines helping in the interpretation of results. Teachers must try to use tools that close the mind of the student more nearly to reality, decreasing the effort for the abstraction processes and using it to comprehend the nature phenomena, processes and algorithms. This article presents how to use Virtual Reality like a tool to teach robotics. Used at the Robotics subject of the Mechatronics Engineering undergraduate course at Universidad Nacional de Colombia and at Mechanisms subject of the Mechanical Engineering graduate course at Universidade Federal do Rio de Janeiro. It is presented the algorithms for kinematics and dynamics of a standard type robot, the robot parts are building in CAD software and translated to a Virtual Reality language (VRML). It is showed the visualization potential of the toolbox of Virtual Reality of MATLAB® working with SIMULINK to simulate de movements of the robot. The algorithms and results are showed, both in Cartesian graphics and the movements seeing in virtual reality windows. It's exposed the advantage of can see directly the movement of the robot parts. Furthermore, it is presented an example of a commercial robot using the CAD parts modeled by the manufacturer and downloaded from its server.

Keywords: robotics, virtual reality, simulation, kinematics, dynamics.

1. INTRODUCTION

Computer technology improves computer results with the help of bigger capacities in microprocessors and memory It is visible by the increment in the number of Flops and processing speed. New software products, developed for the actual computers, allow the design of programs and specialized tools for multiple areas of applications in all fields. These advantages can be used to easily learning of complex knowledge.

The development of computer visualization is an area of principal interest for manufactures, programmers and users. Engineering and entertainment business (games and movies) invest big effort to improve the methods to display three dimensional objects and interact with them.

Virtual reality (VR) is one of the methods to display 3D objects, originally created for use in web publications now supports scientific and educational research and publications. It is based in the Virtual Reality Modeling Language (VRML). The term Virtual Reality Markup Language (VRML) was first used by Tim Berners-Lee at a European Web conference in 1994 when he talked about a need for a 3-D Web standard (The MathWorks, 2008). The software of mathematical calculus MATLAB ® includes a tool for use and edition of VR named V-Realm Builder. VRML processes geometric and positional properties of the objects like dimensions, translation, rotation, color, scale and others.

Computer Aided Design (CAD) is other method for 3D object displaying and manipulation. It was created for use in engineering applications. It is not only for displaying but for model physical properties like mass, mechanical and thermal characteristics. Furthermore, functional and dynamic variables can be manipulated. Many commercial and registered brands are used like SolidWorks, SolidEdge, AutoCad and other are modules in more complex engineering tools like CATIA or ProEngineer.

Displaying objects and its manipulation are based in a big number of mathematical calculations, especially matrix calculations. Then, the use of VR or CAD methods requires fast and efficient mathematical algorithms. Mathematical software tools like MATLAB® or Scilab (GNU software) are used to develop products or solve problems in standalone solutions or in combination with CAD and VR tools.

Robotics learning and design exploits these methods. The VR and CAD tools help the students and engineers to calculate, create and understand the behavior of robots using virtual solutions.

2. ROBOTICS

Robotics basic course studies a introductory knowledge like robot types, components and joints. Then, it is studied the mathematical concepts of rotation and transformation matrices, rotations by Euler and fixed angles. Finally, it is studied the kinematics and dynamics of manipulators.

2.1. Kinematics

A manipulator is represented like a kinematic chain of rigid bodies or links connected by means of revolute or prismatic joints (Scciavicco and Siciliano 2005). To manipulate an object in sapace, it is necessary to describe the end-effector position and orientation.

Direct kinematics describes the position, orientation and movements of the end-effector like a function of the angles of rotation of the revolute joints and the displacement of the prismatic joints. Differential kinematics computes the velocity of ened-effector from the linear and rotational velocities in the joints.

From the relations and transformation matrices obtained in the direct kinematics can be resolved non linear equation systems to compute the rotation angles and displacements of the joints from a desired position and orientatioon of the end-effector. This solution in named the inverse kinematics of the manipulator.

2.2. Matrix representation of the manipulator

Figure 1 shows a generic manipulator, a cartesian frame is atached to every link. The frames goes from **0** or base to **n** or end-effector.
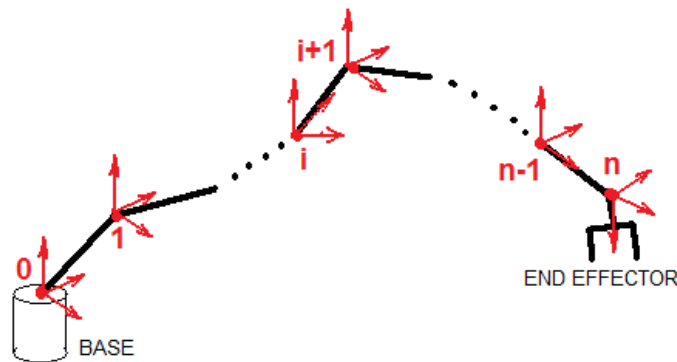

Figure 1. Generic manipulator with frames.

It is builded a transformation matrix to describe the position and the orientation af a frame **i+1** relative to the previous frame **i** (Eq. (1)).

$$_{i+1}^{i}T = \begin{bmatrix} _{i+1}^{1}R & ^{i}P_{O_{i+1}} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}$$

(1)

The transformation matrix has a 4x4 size. $_{i+1}^{1}R$ is a 3x3 rotation matrix and represents the spatial rotation of the frame **i+1** relative to frame **i**. $^{i}P_{O_{i+1}}$ is a 3x1 vector, it has the Cartesian position of the origin of the frame **i+1** measured in the frame **i.**

Equation (2) shows the position and orientation of the end-effector relative to the base of the manipulator.

$$_{n}^{0}T = _{1}^{0}T \, _{2}^{1}T \ldots _{i+1}^{i}T \ldots _{n}^{n-1}T$$

(2)

A transformation matrix may be constructed by two methods. The first one and most used is the Denavit-Hartenberg (DH) method (Craig 1989). The second one is made multiplying partial transformation matrices; every matrix represents a rotation or a displacement along an axis of the reference frame. Equation (3) is the general form of a transformation matrix by the DH method.

3. THREE LINK PLANAR ROBOT

It is a robot with a base and three links joined by revolute joints. It is named as RRR robot, too. The axes of the joints are parallel, consequently the links move in a plane (Figure 2). The model of this robot is normally used to

introduce students in the study of the different stages of a robotics course. It is relatively easy to create its transformation matrices to calculate its kinematics and to draw the results.

$$
{}^{i-1}_{i}T = \begin{bmatrix} c\theta_i & -s\theta_i & 0 & a_{i-1} \\ s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
\tag{3}
$$

θ_i is the i joint angle, $s\theta_i$ and $c\theta_i$ are respectively the sine and the cosine of the joint angle, α_{i-1} is the torsion angle of the link $i\text{-}1$, $s\alpha_{i-1}$ and $c\alpha_{i-1}$ are respectively the sine and the cosine of the torsion angle, a_{i-1} is the length of the link $i\text{-}1$ and d_i is the displacement of the i joint.

3.1. Direct kinematics of the three link planar robot

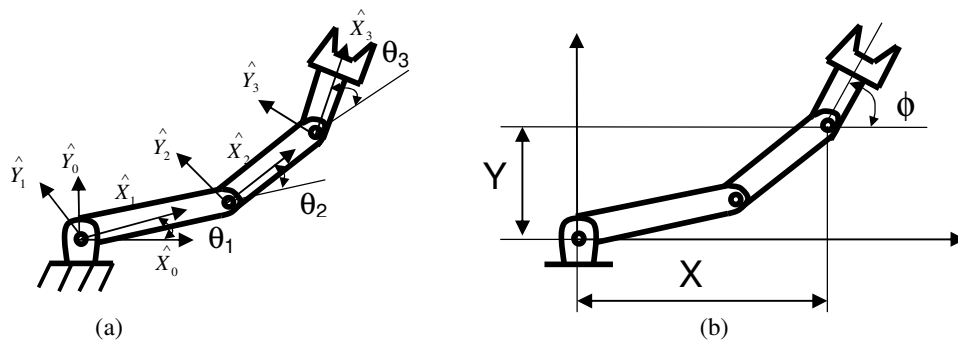(a)   (b)

Figure 2. Three links planar robot.

Figure 2 (a) shows the robot with the joint angles and the reference frames attached to each link. The transformation matrices for each link are calculated using the DH method and with Eq. 2 it is obtained the transformation matrix of the link 3 relative to the link 0 or base. The result is showed in Eq. 4.

$$
{}^{0}_{3}T = \begin{bmatrix} c_{123} & -s_{123} & 0 & L_1c_1 + L_2c_{12} \\ s_{123} & c_{123} & 0 & L_1s_1 - L_1s_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\tag{4}
$$

Where s_1 and c_1 are the sine and cosine of θ_1, $c_{12} = cos(\theta_1 + \theta_2)$ and $s_{12} = sin(\theta_1 + \theta_2)$; $c_{123} = cos(\theta_1 + \theta_2 + \theta_3)$; $s_{123} = sin(\theta_1 + \theta_2 + \theta_3)$; L_1 and L_2 are the lengths of the links 1 and 2.

The coordinates of the origin of the frame 3 and its orientation to the base: $[X, Y, \phi]^T$ are calculated from a set of given joint angles $[\theta_1, \theta_2, \theta_3]^T$ (Figure 2 (b)). Different drawing aids can be built to demonstrate these relations and results to the students. Figure 3 shows a GUI (Graphics User Interface) made with MATLAB to generate a line sketch of the robot. Entry data are the three joint angles given using the slider controls.

3.2. Inverse kinematics of the three link planar robot

From the Fig. 2 (b) it is calculated the transformation matrix of the end-effector to the base of the robot. The result is Eq. (5).

The matrix in Eq. (4) is equivalent to matrix in Eq. (5). The equivalence of the elements of the two matrices gives the nonlinear system of equations showed in Eq. (6). The input data is $[X, Y, \phi]^T$ and the unknowns are the joint angles.
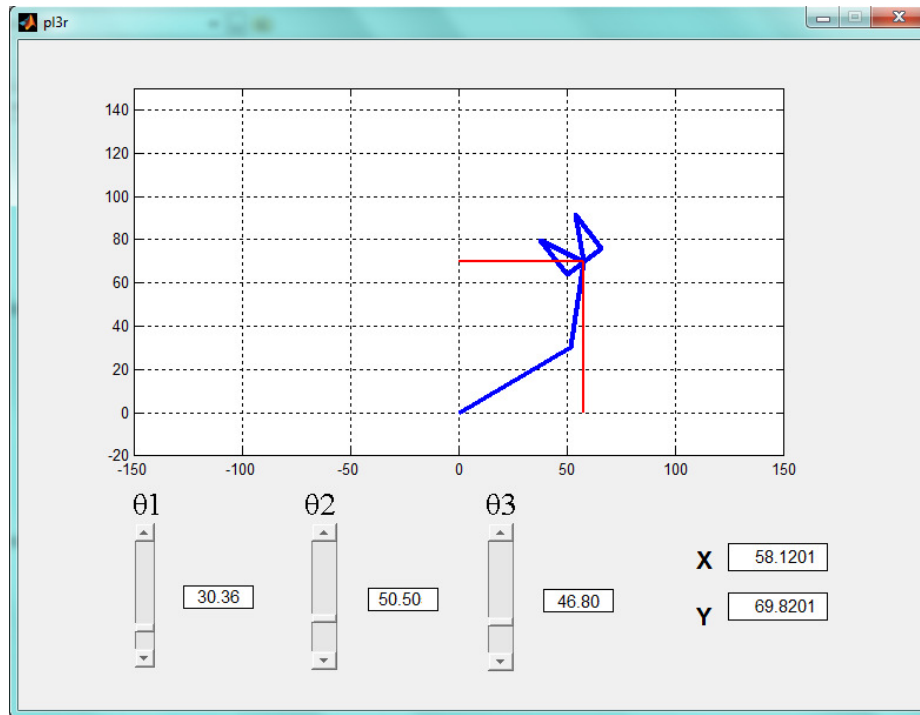
Figure 3. GUI to show the direct kinematics of the 3 links planar robot.

$$
{}^{B}_{G}T = \begin{bmatrix} c\phi & -s\phi & 0 & X \\ s\phi & c\phi & 0 & Y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\tag{5}
$$

$$
\begin{cases} X = L_1 c_1 + L_2 c_{12} \\ Y = L_1 s_1 + L_2 s_{12} \\ \phi = \theta_1 + \theta_2 + \theta_3 \end{cases}
\tag{6}
$$

The system has two types of solutions: closed solutions or numerical solutions. The first type may be algebraic or geometric and second type uses numerical methods. When a closed solution is obtained, its application is faster than the numerical solution.

An algebraic solution is given in the Equations (7) to (9).

$$
\begin{cases} \theta_2 = a\tan 2(s_2, c_2) \\ c_2 = \dfrac{X^2 + Y^2 - L_1^2 - L_2^2}{2L_1 L_2} \\ s_2 = \pm\sqrt{1 - c_2^2} \end{cases}
\tag{7}
$$

$$\begin{cases} \theta_1 = a\tan 2(s_1, c_1) \\ c_1 = \dfrac{X(L_2 s_2) + Y(L_1 + L_2 c_2)}{X^2 + Y^2} \\ s_1 = \dfrac{X(L_1 + L_2 c_2) - Y(L_2 s_2)}{X^2 + Y^2} \end{cases} \tag{8}$$

$$\theta_3 = \phi - \theta_1 - \theta_2 \tag{9}$$

These equations obtain the set of joint angles for a position and orientation of the link 3. The robot is moved tracking a desired trajectory with an iterative use of the solution by mean of structured programming, this is a more interesting application.

4. USE OF VIRTUAL REALITY

Movements of the robot can be displayed using simplified line sketches, but the students obtain an improved comprehension of the results when the visualization is more closed to the real image of the robot. To obtain this, links and robot models are built with Virtual Reality (VR) or similar tools.

Models of every link were created using the CAD tools SolidEdge® and SolidWorks®. Then, the links were assembled to form the complete robot. The mate operations between parts allow the verification of the movements of the robot model.

The software exports the CAD models to a VRML format to use them with VR software later. The model is opened with the software V-Realm Builder. The movements of the model are verified and adjusted if it is necessary. Some improvements are used like addition of lights or cameras to watch the model from multiples points of view.

MATLAB and SIMULINK can be linked to the VRML model and control it. For control, values of the variables are calculated with MATLAB programs or with SIMULINK models; they are send to the model and modify some properties of the parts. For robot's simulation the properties controlled are "translation" and "rotation", it results in changes of the position and orientation of the parts. The coordinated movements of the parts show the behavior of the entire robot.

Figure 4 shows a SIMULINK model to control movements of the 3 links of planar robot, the block named VR sink represents the VR model. This block receives the signals of the variables calculated by the other blocks.
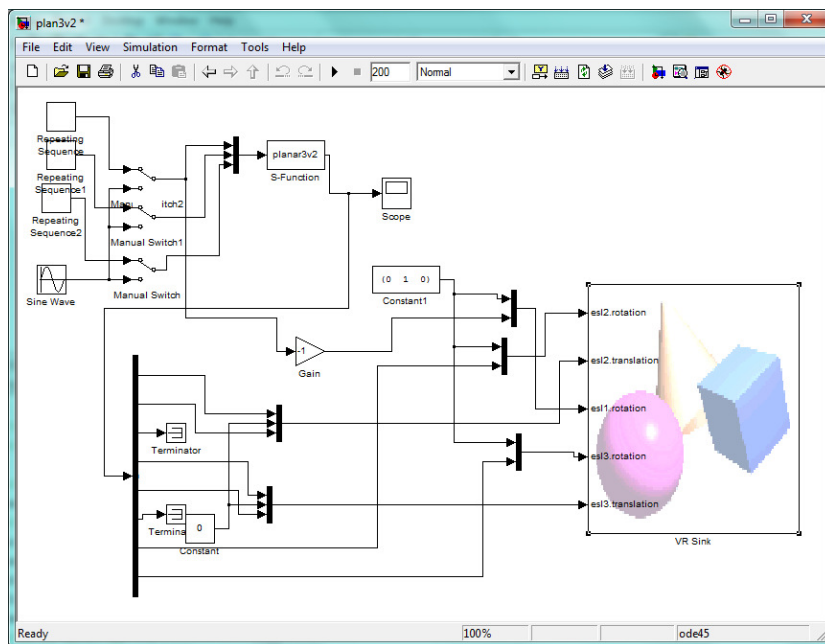

Figure 4. Simulink model with a VR model embedded.

The signal for translation is a vector of size 3x1 with the X, Y and Z coordinates of the centroid of the part controlled. The vector to control rotation has a 4x1 size. The first three, are the components of an axis of rotation and the fourth value is the angle rotated about the axis. This method of representation corresponds to the concepts of screw axis representation (Tsai, 1999) or equivalent angle-axis (Craig 1989).

When the program or the model is running, a window is open with the VR model and shows the simulation of the movement of the robot. The user can use some advantages of the VR displays like switch between cameras or change the speed of the simulation. Figure 5 shows the VR display with its controls and Fig. 6 shows a sequence of positions of the three links planar robot during a simulation.
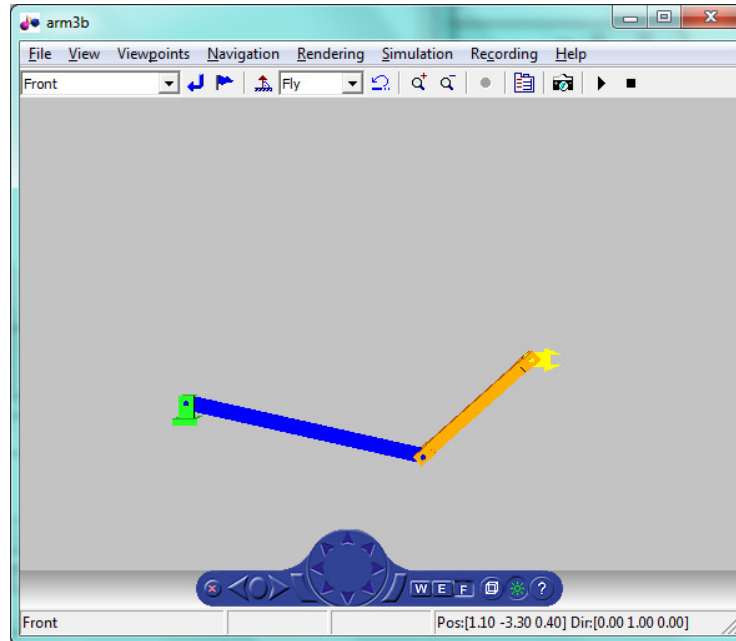

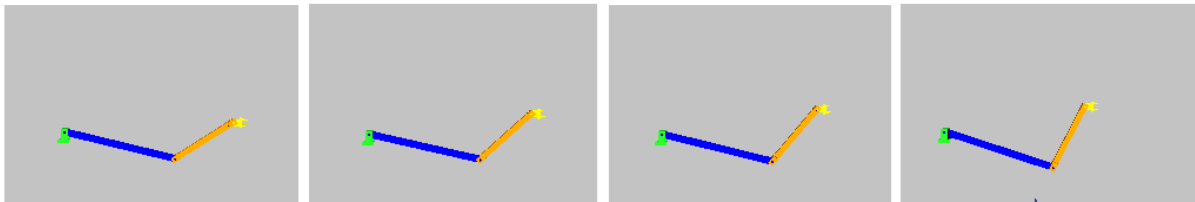**Figure 5. VR display for the three links robot arm.**

Figure 6. Positions during a simulation.

5. SIMULATION OF A COMERCIAL ROBOT

The method described above is used to simulate commercial robots. LabRob, robotics laboratory of the Mechanical Engineering Program at Federal University of Rio de Janeiro, has a robot of the brand KUKA® Robots for teach and experiment in manipulator robotics. The model of the robot installed had changed from time to time.

From website of the robot manufacturer can be downloaded the CAD models of the products. For example, was downloaded the model KR16 (KUKA Aktiengesellschaft, 2010), then was converted to VR format and was connected to a SIMULINK model. The simulation permits to the students use the virtual model to simulate movements, watch and analyze the results. When the real robot is programmed the real and virtual movements can be compared.

Figure 7 shows the VR display with the model of the robot KR16 and the Fig. 8 shows the sequence of joint angles applied to the model for a rectangular movement of the end-effector in a horizontal plane.
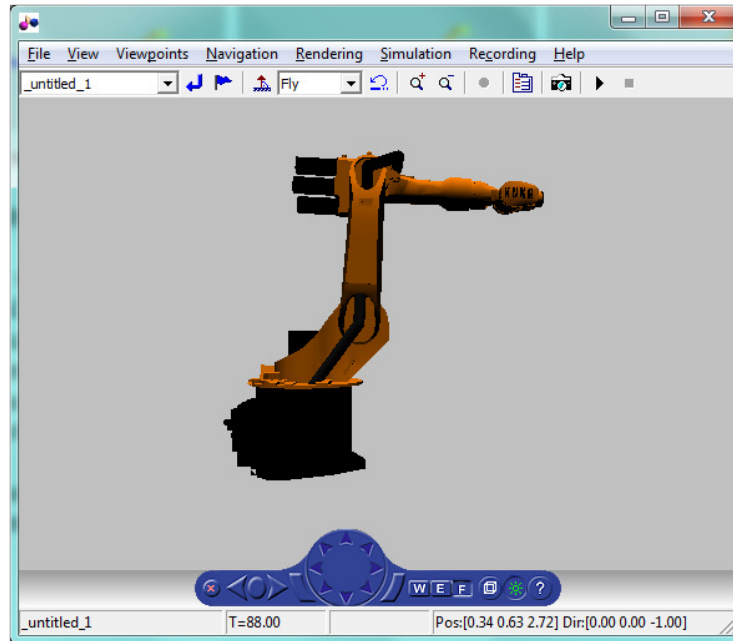
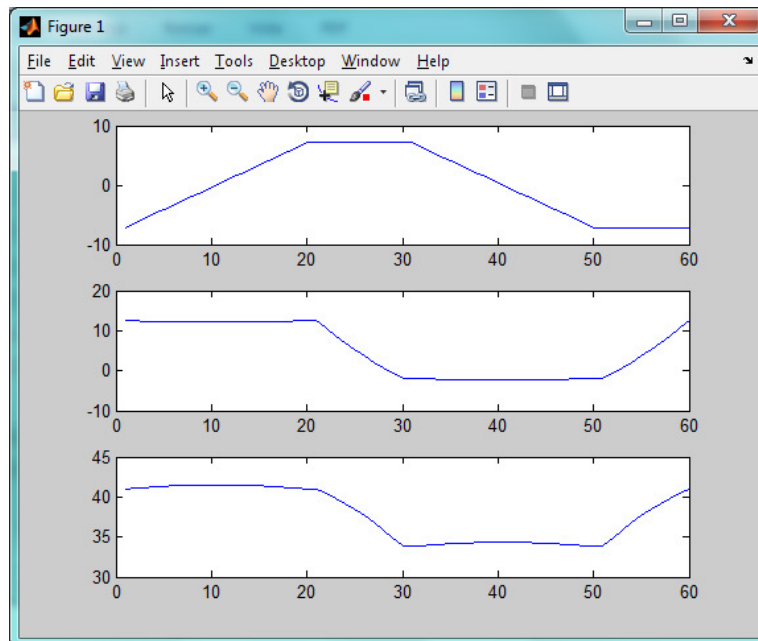**Figure 7. VR model of a commercial robot.**

Figure 8. Sequence of joint angles.

6. CONCLUSIONS

It was used kinematics and dynamics mathematical tools of mechanisms for teaching the behavior of robots and for the calculation of the motion variables. The movement variables, linear and angular, and the forces and torques existing in manipulators can be formally represented as tables or graphs. Students gain a better understanding of the behavior of robots when they used and present simulations of the movements on the computer screen.

Simple and complex robots and commercial models were studied through class exercises and assignments in the subjects mentioned in this work. The theory was applied to classroom exercises with two and three links planar robots. As homework and subject project were studied Puma, Stanford and commercial type robots. These exercises included the simulation of movements. An increase in student's interest in the study of robotics was denoted as much exercise simulations of movement they applied.

To simulate the movements were used two main forms of representation. In the first one the links were represented in a simplified form like straight lines, triangles or rectangles. The second one used representations of type 3D modeled parts in CAD or virtual reality language. For the simulation were used computer programs like Simulink ™ with the toolbox for virtual reality applications, commercial CAD and some proprietary software of robot manufacturers. For assessing the interest of students in different courses were used: a counting of the number of assignments presented with the first or second method of representation, interviews and questionnaires to students at the end of the courses.

Students in percentages above 90% said benefits in understanding and applications with the use of 3D representations, demonstrating the usefulness of this method of representation in teaching of robotics in engineering courses.

7. REFERENCES

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8. RESPONSIBILITY NOTICE

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