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Three Degrees of Freedom Robot Arm with Augmented Reality Markers for Education and Training Courses in Robotics

Martín Montes Rivera and Humberto Velasco Arellano

***Abstract*—Robotics with artificial intelligence is an essential basis of industry 4.0, where intelligent robots with full-time connectivity react to flexible manufacturing, sharing workspaces with working employees and other machines. De-signing these robotic systems with artificial intelligence and applicable to all manufacturing processes implies knowledge of experts in computer science, physics, mechanics, and industrial processes, among others whose previous knowledge in robotics is minimal. The lack of space perception in a three-dimensional world is a common difficulty for those who start working with robots, and missing attendance to this problem can produce several injuries and high-cost damages. Alternatively, employees and designers can work with augmented reality robots to solve this problem since Augmented Reality is another critical technology in industry 4.0. However, students must work using basic libraries to solve the pose estimation problem and render three-dimensional objects by applying the mathematical background of robotics and Augmented Reality instead of commercial libraries that deal with the situation as a black box solution. This alternative lets the students understand the background problem and design their new technologies. In this work, we propose using an Augmented Reality with markers for rendering a robot arm that shows frames, moving direct, and inverse kinematics once the students provide the Denavit–Hartenberg convention that correctly describes the robot. First, we estimate the robot pose by determining the homography matrix between the initial position and the current frame acquired from the camera. Then we modify the position and orientation of the rendered robot with all its frames and graphical information. Finally, we render the robot in the Webots environment to simulate robots.**

***Index Terms*—Augmented reality, robotics, kinematics of robots, industry 4.0, education.**

I. INTRODUCTION

Today, education is evolving with the speed at which Internet users consume information [1,2]; this conditions the cognitive and intellectual development of the new generations [3,4]. In addition, physics is a science that requires a high level of imagination and interpretation of the environment and the interaction of the objects of study [5,6].

In this field, the use of Augmented Reality (AR) allows bringing the user the comfort of visualization, providing an additional perspective on the conventional method [7,8]. Some studies report an improvement in attention and engagement with learning, an essential tool for education and training for Industry 4.0 [9,10].

Within Industry 4.0, the use of robots stands out due to their broad flexibility and ability to adapt their work in flexible manufacturing processes, allowing production to meet constantly changing needs [11–13].

On the other hand, the constant use and manipulation of robots flexibly take relevance, bringing significant challenges in training personnel accustomed to the previous industry, seeking to make a smooth knowledge transition. At the same time, new generations must possess these skills to incorporate into Industry 4.0 [14,15].

Moreover, new jobs integrate industry 4.0 technologies, such as the internet of things [16], simulators [17], horizontal and vertical integration [18], autonomous robots [19], and cybersecurity [20].

In the same way, working with AR exhibits good results when tested in mathematics, chemistry, biology, astronomy, and physics, among others, evaluating the performance and acceptance of students [21–23].

Additionally, simulators for science facilitate the visualization of typical engineering problems and reduce the complexity of final implementations [24].

In this work, we propose an augmented reality simulator to support learning and training in robotics, allowing us to visualize and control a robot with the effects of direct and inverse Kinematics in robots while training students with the Denavit-Hartenver convention, in this case, for an angular robot with 3 Degrees Of Freedom (DOF).

A. State of the Art

In education, AR with markers allows interaction with didactic material associated with a subject and limits its use to a marker that can be moved or duplicated for its portability [25,26].

Similarly, AR allows the generation of meta-knowledge, showing graphically physical and mathematical experiments, promoting consolidation of critical thinking [7].

Moreover, AR also improves the spatial intelligence of students with three-dimensional content, like perceiving mathematical functions [27].

Additionally, AR is an efficient resource that can be shared through open sources such as communities on the web, allowing teachers and students to create new digital content. With AR, learning can develop faster through rich interaction with knowledge, which increases student motivation [28].

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The autors are with the Universidad Politécnica de Aguascalientes, Maestría en Ciencias en Ingeniería, Mexico (martin.montes@upa.edu.mx, humberto.velasco@upa.edu.mx).

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TABLE I
STATE OF THE ART OF AR IN ROBOTICS AND TRAINING COURSES

No	Title	Develop	Application
1	Augmented Reality: A Systematic Review of Its Benefits and Challenges in E-learning Contexts [30]	Review the benefits and challenges of using AR and the increased motivation and commitment to the subjects.	Multidisciplinary students analyze AR support for theoretical subjects.
2	Augmented Reality and programming education: A systematic review [31]	Review of AR applications in early childhood education and knowledge development.	AR applied in basic education subjects and the impact on the learning curve.
3	Augmented reality and competition in robotics education: Effects on 21st-century competencies, group collaboration and learning motivation[32].	The positive effects of the application of AR in the development of mobile robots are analyzed.	A group of students learns to program with AR, improving collaborative skills and motivation.
4	Towards an Augmented Reality Framework for K-12 Robotics Education[33]	AR application to integrate mobile robots and vision into route planning.	Applying AR utilizing markers to identify possible obstacles and modify the route plan to avoid collisions in a mobile robot equipped with vision.
5	An Education Application for Teaching Robot Arm Manipulator Concepts Using Augmented Reality [34]	Use AR for didactic work teaching basic robotics concepts.	AR uses a virtual protractor to identify each joint's angles on a robotic arm.
6	Utilizing virtual and augmented Reality for educational and clinical enhancements in neurosurgery [35]	Use of AR in virtual practices of neurosurgical clinical cases	AR increases understanding of the neurosurgical procedure in pre-practice students.

On the other hand, the use of robotic manipulators with AR in Industry 4.0 allows capacitating professionals on the demands of constant change in production lines, working under the philosophy of flexible manufacturing, adapting the process to a technological group of parts, and making efficient production on demand [13].

Similarly, AR allows testing industrial robots to perceive them interacting in different environments and conditions before installation, improving the design stages [29].

Table 1 shows a brief description of the works we found relevant to our proposal of using AR with robotics to improve the training of students in direct and inverse Kinematics using a 3DOF robot.

Moreover, the mix of robotics with AR in education showed that augmented systems with the joints-position in real-time motivates students and improve the design stage and comprehension of students of robotics [36].

II. THEORETICAL FRAMEWORK

A. Augmented Reality

Augmented Reality (AR) is the term used to describe the technology that allows visualizing part of Reality through a device, adding graphical information, thus augmenting the one perceived in the environment. In other words, this technology adds virtual information to the physical one, allowing Reality to interact with virtual data [21].

Among the different approaches for augmented Reality, one of the most precise in nonstereoscopic vision is the vision with tracking of detection of markers [37]. There are different levels of AR [38]:

- Level 0. Links with links through QR codes.
- Level 1. AR with markers, using objects a camera identifies to activate the associated AR.
- Level 2. AR without markers, in this case, the AR is usually activated with the use of GPS and accelerometers.
- Level 3 Augmented Vision can be associated with applications such as Google Glasses.

AR with markers, as used in this work, implies knowing the basic principles of transformation between reference planes used for camera calibration. There are different methods for that [39]. However, the homography matrix (H) simplifies and solves the problem of obtaining the transformation matrix from C_1 to C_2 with the scaling factor (s). This work identifies AR markers' points in a plane image which is the basis for the markers, and later in a frame acquired with the camera (Fig. 1) as in equation (1) [40,41]. Thus, the homographic matrix transforms a flat marker, correcting the uncertainty and measuring the perspective by comparing the points in the model and those in the camera image [39]. Thanks to this, it is possible to use flat markers as AR triggers:

$$s\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \mathbf{H}\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}. \quad (1)$$

The intrinsic parameters relate the measurements of the scene with the measurements obtained in pixels; for this purpose, a transformation matrix for knowing the size of a flat object in pixels; this characteristic is specific to each camera and includes as parameters: focal length, aperture, the field of view, and resolution [41].

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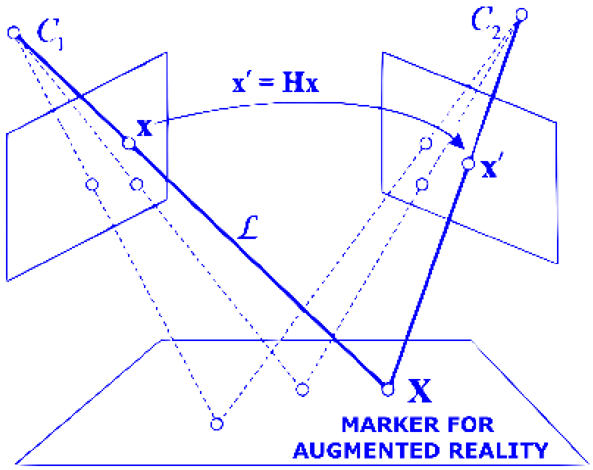

Fig. 1. 3 Use of homography matrix for camera pose estimation

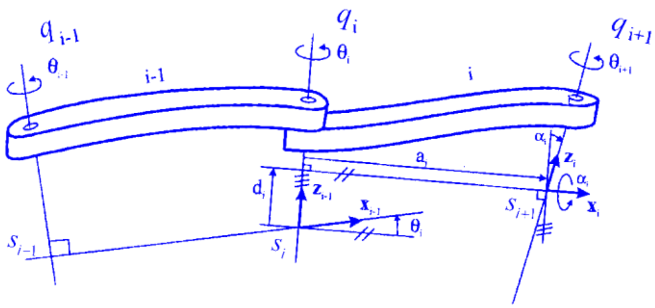

Fig. 2. Kinematic chain following the Denavit-Hartenberg convention

The extrinsic parameters relate the measurements of the scene with the image obtained, depending on the projection; those extrinsic parameters include the pose estimation information, that is, the position and orientation of the camera [42].

The homography matrix contains the intrinsic and extrinsic parameters of the camera with the pose transformation moving from all the points in the plane C_1 to C_2, and considering that the base image has 0 value for all its points in $\mathbf{X}$ since it is in a plane image, we get the equation (2), where $\mathbf{P}$ is the pose of the marker and $\mathbf{K}[\mathbf{r}_1 \quad \mathbf{r}_2 \quad \mathbf{r}_3 \quad \mathbf{t}]$ are the intrinsic and extrinsic parameters of the camera:

$$\mathbf{PX} = \mathbf{K}[\mathbf{r}_1 \quad \mathbf{r}_2 \quad \mathbf{r}_3 \quad \mathbf{t}]\begin{pmatrix} X \\ Y \\ 0 \\ 1 \end{pmatrix}. \tag{2}$$

B. Robot Kinematics

The Kinematics of a robot describes its position and movement for a reference axis. In this way, encoders measure the position of the joints controlled by motors, which vary the end effector's location without considering the effects of mass and dynamic forces, which are unexistent in augmented reality models. This study is known as Forward-Kinematics (FK). When working with robots (FK), as in this case, the Denavit-Hartenberg (DH) convention and rotation matrices obtain the position and orientation of the robot's end effector [43].

The DH algorithm uses 17 steps defined in [44] for identifying the links l_i, joints q_i, and systems s_{i-1}, as shown in the kinematic chain in Fig.1. After assigning them, the DH transformation matrixes ${}^{i-1}A_i$ defined in the equation (3) in terms of the DH parameters: a rotation in the "Z" axis given by θ_i, a translation in the "Z" axis given by d_i, a translation in "X" axis given by a_i, and a rotation in "X" axis given by α_i [44]:

$${}^{i-1}A_i = \begin{bmatrix} C\theta_i & -C\alpha_i S\theta_i & S\alpha_i S\theta_i & a_i C\theta_i \\ S\theta_i & C\alpha_i C\theta_i & -S\alpha_i C\theta_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{3}$$

The multiplication of the DH transformation matrixes from the basis up to the end effector obtains the transformation matrix containing the end effector position and orientation, as shown in the equation (4) [44]:

$${}^{0}A_e = {}^{0}A_1 \times \ldots \times {}^{i-1}A_i \times {}^{i}A_{i+1} \times \ldots \times {}^{e-1}A_e. \tag{4}$$

On the other hand, inverse Kinematics determines the position of the motors starting from a desired final effector position. Achieving this goal implies the matrix operation described in the equation (5) to perform algebraic substitutions for obtaining the equations that find required q_i values for desired positions and orientations in the end effector [44]. Alternatively, one could use optimizing algorithms to find the q_i values that satisfy the desired end effector position and orientation [45]:

$${}^{e}A_0 = {}^{e}A_{e-1} \times \ldots \times {}^{i+1}A_i \times {}^{i}A_{i-1} \times \ldots \times {}^{1}A_0. \tag{5}$$

III. Methodology

We start by determining the direct Kinematics of the model by obtaining the frames of parameters according to the DH convention in section 2.2. After that, we compute the direct kinematics formula to obtain three equations for varying the position of the end effector. We omit other equations for orientation because the robot only has 3 DOF, and we need 6 to control it, like in the equation (6):

$$\begin{aligned} x &= f_x(q_1, q_2, q_3, q_4, q_5, q_6), \\ y &= f_y(q_1, q_2, q_3, q_4, q_5, q_6), \\ z &= f_z(q_1, q_2, q_3, q_4, q_5, q_6), \\ \alpha &= f_\alpha(q_1, q_2, q_3, q_4, q_5, q_6), \\ \beta &= f_\beta(q_1, q_2, q_3, q_4, q_5, q_6), \\ \gamma &= f_\gamma(q_1, q_2, q_3, q_4, q_5, q_6). \end{aligned} \tag{6}$$

For the inverse kinematic model, we solve the no linear equations with the structure on 6 using Fsolve of Scipy library in Python that applies least square optimization on the function we defined for finding the correct joint position (q_1, q_2, q_3) for a desired position in the end effector (x_d, y_d, z_d):

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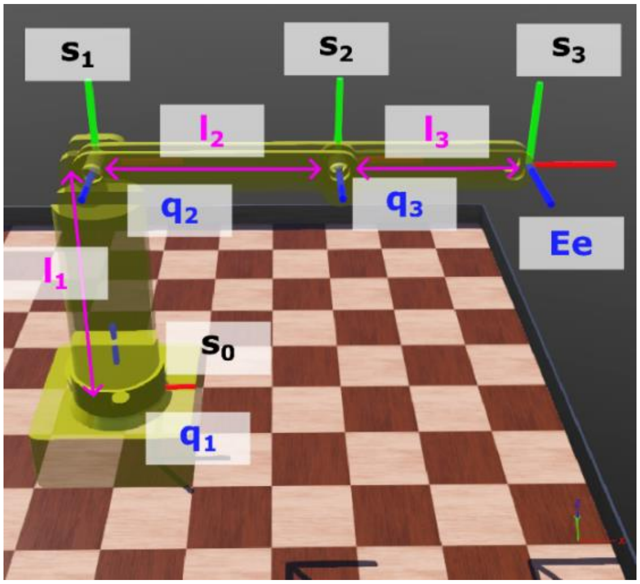

Fig. 3. Information of angular robot analyzed under Denavit-Hartenberg convention

TABLE II
DENAVIT-HARTENBERG PARAMETERS FOR A 3 DOF CYLINDRICROBOT

Frame	DH matrix	θ_i	d_i	a_i	α_i
$s_0 \rightarrow s_1$	A_1^0	q_1	h_b	0	0
$s_0 \rightarrow s_1$	A_2^1	0	l_1	0	90^o
$s_1 \rightarrow s_2$	A_3^2	q_2	-0.038m	0	0
$s_2 \rightarrow s_3$	A_4^3	q_3	0	0	0
$s_2 \rightarrow s_3$	A_5^4	0	0.038m	l_3	0

Fig. 4. Model points obtained with ORB descriptor using OpenCV 2 library

$$F(q) = \begin{bmatrix} f_x(q_1, q_2, q_3) - x_d \\ f_y(q_1, q_2, q_3) - y_d \\ f_z(q_1, q_2, q_3) - z_d \end{bmatrix}. \quad (7)$$

With the optimization function:

$$min_{\,x} \frac{1}{2} \|F(x)\|_2^2 = \frac{1}{2} \sum_i f_i\,(x)^2. \quad (8)$$

After that, we continue with the augmented reality application that acquires a picture of the base image and computes the model with the ORB algorithm using the OpenCV 2 library for python. The ORB algorithm uses Binary Robust Independent Elementary Features (BRIEF) descriptors based on corner detectors, and Features from the Accelerated Segment Test (FAST) used to detect features from the provided image. ORB improves orientation perception by rotating according to the orientation of points perceived, as detailed in [46].

Ones we process the model, we know the interest points for detecting the image, and then we measure the distance between these points and those in the frame captured with the camera to determine if they belong to the base image.

If they belong to the image, we compute the pose and pass it to render de models in the simulation environment, a Webots world. We selected this environment because it is the most used framework for robotics simulations in SimGait, Dexter, ROSin, Samsung, Siemens, Sony, Toyota, and universities like Boston, Harvard, Columbia, Berkeley, Oxford, and Michigan, among others.

IV. RESULTS

A. Design of Experiment

We programmed the image processing framework, and the graphical user interface as the direct and inverse Kinematics of the robot in python 3.8.10 on a Laptop Dell Latitude 3580 with Windows 10 21H2 19044.2130 with Intel(R) Core (TM) i5-6200 CPU @ 2.30GHz with 8 GB RAM. The camera used was a Logitech c920 with a resolution configuration of 640x480.

B. Denavit-Hartenberg Analysis

Fig. 1 shows the results of analyzing the 3 DOF angular robot used in this work under the DH convention, marking the links l_i, the joints q_i, and the frames s_{i-1} corresponding to each degree of freedom, in this case $i=3$.

With these graphical data, we can generate Table 1 containing the DH parameters $(\theta_i, d_i, a_i, \alpha_i)$ from the s_0 robot base frame up to the end effector frame s_3, and with them, we get the transformation matrixes for rendering in Webots the links according to the frames in Fig. 3.

With these matrixes, we get the f_x, f_y and f_z in equations (9) to (11) by multiplying according to the equation (4) in section 2.2. With these equations, we get the end effector position for direct Kinematics and the joints for the desired position by solving them according to the equation (7).

$$f_x = 700.0\,cos(q_1)\,cos(q_2) + 550.0\,cos(q_1)\,cos(q_2 + q_3), \quad (9)$$

$$f_y = 700.0\,sin(q_1)\,cos(q_2) + 550.0\,sin(q_1)\,cos(q_2 + q_3), \quad (10)$$

$$f_z = 700.0\,sin(\,q_2) + 550.0\,sin(\,q_2 + q_3) + 1000.0. \quad (11)$$

C. Augmented Reality Results

Finally, we obtain the model for AR with the image characteristics obtained using the base image and the ORB descriptor with OpenCV 2 library. With this model, we obtained the descriptor points (Fig. 4).

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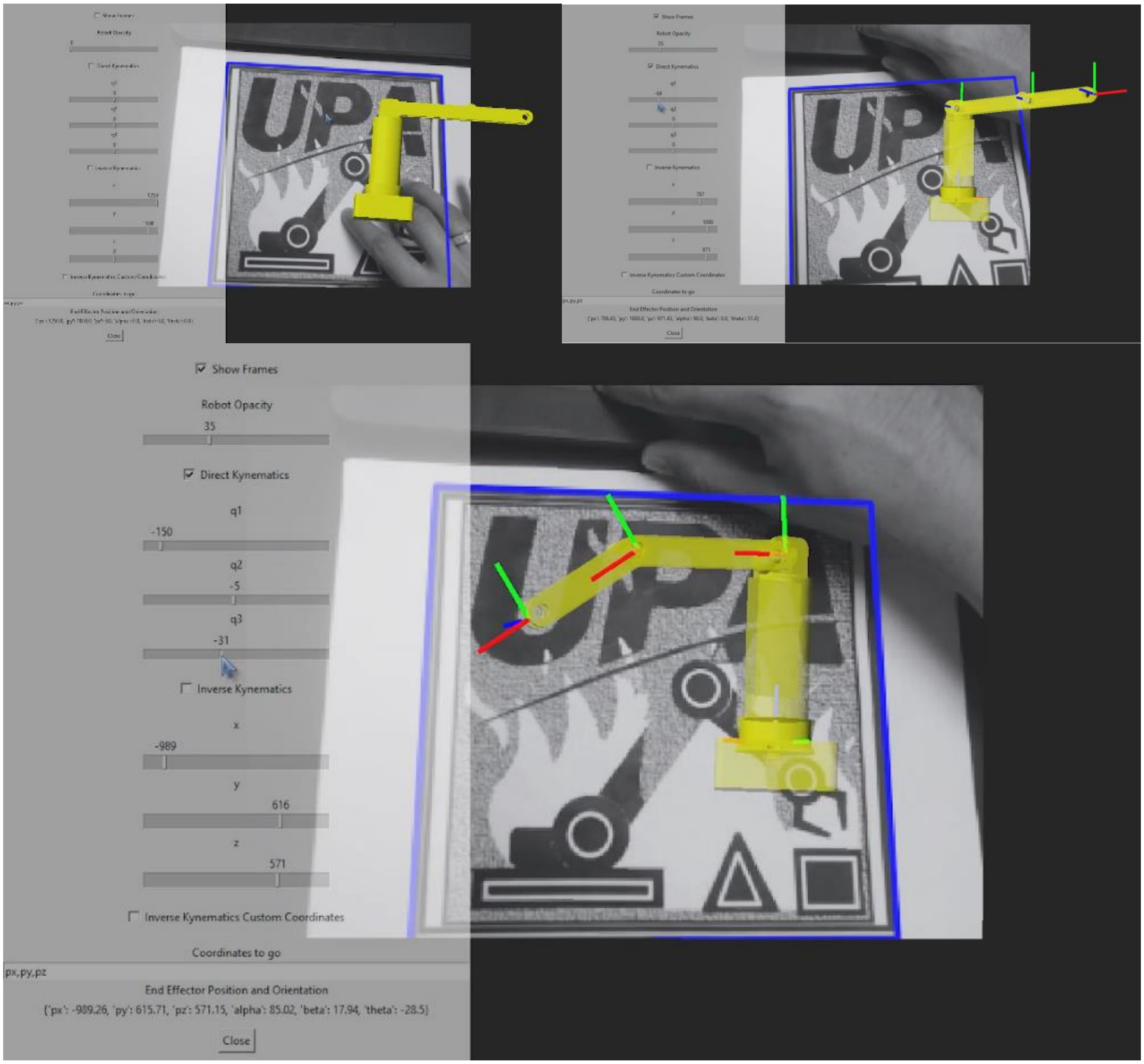

Fig. 5. Captures of proposed AR interface for rendering 3DOF robot varying marker position

After that, we acquired the model based on the camera images. Then, we compute the homography and the pose of the image $\mathbf{P}$, which we use to assign the origin of the frame s_0 in the 3 DOF robot for rendering in Webots. The captures we get from the interface while varying the position of the base image or marker are in Fig. 5.

In the graphic interface, we allow the user to control with slides and checkboxes the opacity of the robot and the frames per joint. Additionally, we use slides and a text box to control the direct and inverse Kinematics, as shown in Fig 6.

The entire process of acquiring the images and rendering the robot with the conditions established in the user interface achieved real-time with 31.25 Frames per Second (FPS).

V. Conclusions

In this work, we develop a real-time augmented reality simulation to improve the understanding and study of robots and their Kinematics with robotics students. For this, we propose to build a 3DOF robot to visualize the behavior and meaning of the mathematics corresponding to the direct and inverse Kinematics. The augmented Reality in this application uses an AR marker processed with an image and the ORB descriptor implemented in OpenCV 2 library and python to obtain the model base. After that, we process camera images with ORB descriptor, and then we use homography between the model image and the acquired images to estimate the marker's pose and render the robot with that mark.

The students must propose the DH transformation matrices in a txt file, and with this tool, the students can render a robot model and upload its mathematical results, visualizing if their mathematical description is correctly defined.

In this way, we found that AR allows us to implement an interface in which students could generate meta-knowledge regarding the area of robotics, being a human capital with an added value aligned with the needs of industry 4.0

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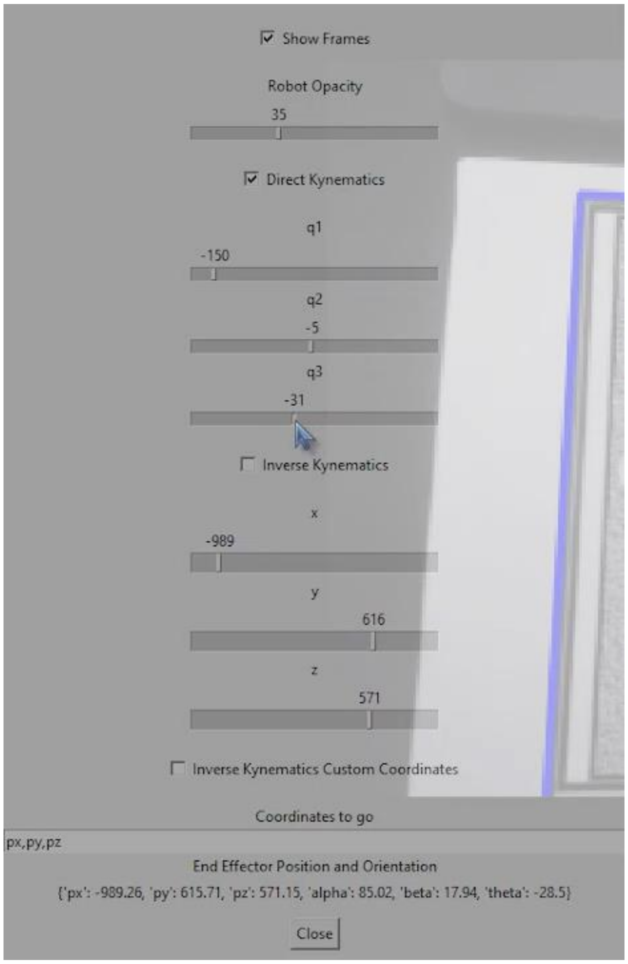

Fig. 6. 3 Interface controls for proposed AR application to render 3DOF robot to help students understand Kinematics of Robots concepts

VI. Future Work

Up to this work, we have implemented the interface and AR system. However, this is not a sufficient probe for the benefits reached. Thus, we will evaluate the correlation between educational improvements in the Kinematics of robots and our proposal with quantitative instruments like the result of previously validated exams and statistical correlation measures in control and experimental groups.

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