Numerical methods for handling robotic arms using augmented reality

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Abstract. This document presents an augmented reality application for mobile devices, as a contribution to education through a technological learning tool that allows the management of industrial robotic arms, implementing advanced control algorithms, which allows the simulation of several selected desired trajectories by the user; and the incorporation of animations that allow to know its operation and to verify the follow-up of the proposed trajectory, as well as the visualization of control errors in each trajectory taken. The application is oriented to the simulation of industrial robotic arms within an intuitive and friendly augmented reality environment, which allows users a great interaction with the robot's structure, providing simulation programs with new immersion technologies, in the educational field. Tests in the augmented reality application demonstrate ease of use and user intuition, providing a better understanding of the operation and structure of programmable manipulators.

Keywords: augmented reality, industrial robots, 3D animation, numerical control methods.

1 Introduction

Education in recent years has been developing new milestones and ways of teaching, the use of new technological tools immersed increases the interest and learning experience [17], these tools allow the student to interact with the environment, naturally promoting their interest in discovering things [4]. The development of AR and VR applications has increased enormously in the last decade, these technological tools have as main axis, the interaction of the user with a virtual environment, the great difference is that the augmented reality provides the user a mixed, approach since it allows manipulating the virtual environment through a technological device without leaving the physical world [12]. The applications in a virtual environment are huge because it allows the construction of any object without being limited by dimensions, which causes that students have new learning tools in different contexts and topics [14].

AR applications are developed for specific tasks [9], and can be grouped into two main groups. Firstly, the applications focused as training assistants [7; 10; 11; 15; 18], are applications that provide step-by-step assistance for manual assembly processes, [15] compare the impact of AR assistants with video-based assistants, concluding that it reduces the amount of errors in production, and operation failures due to erroneous maneuvers, requiring less effort to memorize the execution steps, in addition to optimizing the time of training or onsite courses in the field. The use of AR assistants has a wide range of uses, allowing users to interact with different processes, whether educational or industrial, among others. Authors of [8] presents a system that allows collaboration to collaborate in real time to successfully carry out a mechanical maintenance task, this system unites the paradigmatic interaction that allows simulating the presence of the expert with an operator in an assistance situation.

Second, the entertainment applications [3; 6; 13; 16]. In [3] presented an application intended to teach the metabolism of the human body, especially the metabolism of glucose. The application is full of animations that provide a very immersive and very realistic environment, allowing the understanding of metabolism, from the moment food enters the mouth and its respective journey through the digestive system. Article [16] describes an AR game based on vision and interaction with non-contact movements, in which users through dynamic hand and foot gestures, interact with the virtual elements of the scene in front of a camera, activating an event of interaction predefined. Author of [6] makes an analysis of what are the technological, pedagogical characteristics of mobile AR games focused on education, there they describe characteristics about Calory Battle AR, a location-based game that combines physical exercise with possibility to include educational content, and Leometry which is a story-based geometry learning AR game.

This work aims to assist in learning about industrial robots through the development of an AR application. The application allows the visualization of the components of the manipulators by means of animation and visualization of multimedia files through the 2D recognition of identification codes, as well as the simulation of the behavior of the robot structure through the implementation of advanced control algorithms that allow the mobility of the operating end towards the path desired by the user.

This work is divided into IV sections, the first section includes the *Introduction*, the second section called *Development*, details the detection technique used, the characteristics of the mobile application environment and the laws of closed loop control, the third section details the *Results obtained* when using the AR application through a smartphone with its respective analysis of results and, finally, the fourth section describes the *Conclusions* of the work done.

2 Development

The proposed workflow diagram for the creation and development of the AR application is shown in figure 1, it considers five main stages with a specific task each, plus one or more processes that allow to execute the workflow tasks of the application for the smartphone:

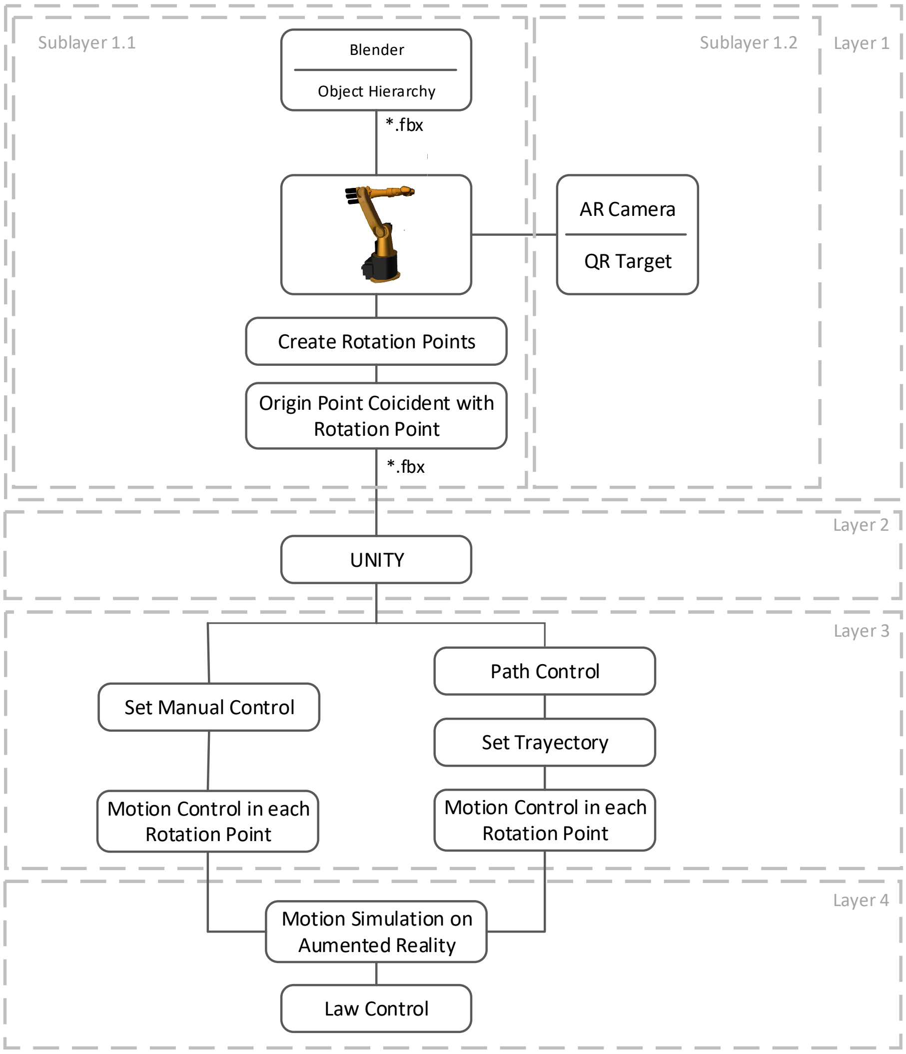

Fig. 1. Mobile application development workflow diagram.

i) Layer 1.1 allows 3D development using Blender software, which is a program specifically designed for the development of 3D objects, rendering, animation, special effects, etc. [5]. The 3D model of the robotic arm is shown in fig. 2, in which each of the elements or parts is made to coincide with the rotation points, in order to generate a correct movement of the elements within the Unity platform; the file is exported in *.fbx format.

ii) Layer 1.2 describes the 2D recognition technique, which allows the detection of images and text. This image is loaded into Vuforia Developer Portal's Target Manager, which allows the creation of databases and the generation of a Unity-compatible file, as seen in fig 3. Vuforia processes each image and generates characteristic points, according to these characteristic points the recognition quality is given. Fig. 4 shows the standard image to be used and fig. 5 shows the image characteristics that will determine the recognition quality.

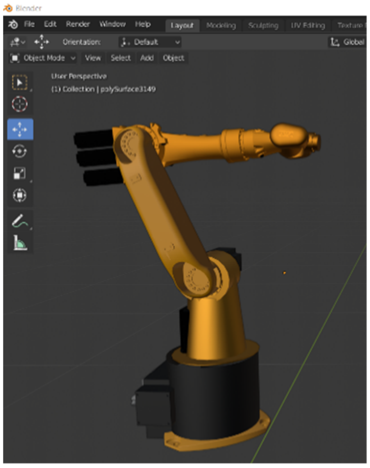

Fig. 2. 3D model of the robotic arm in Blender.

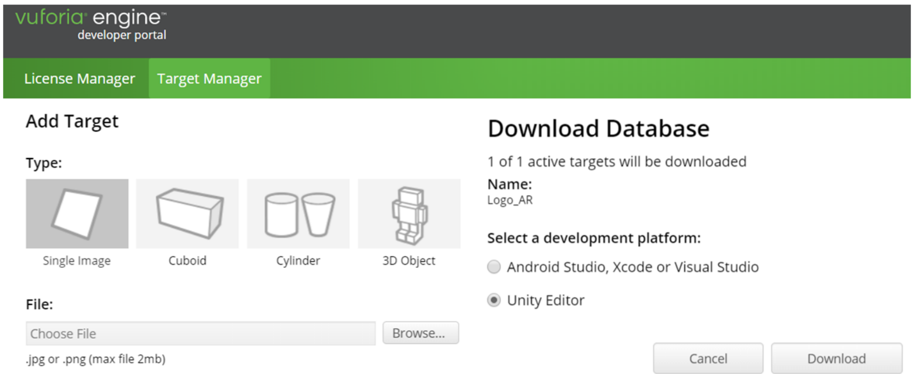

Fig. 3. Vuforia Developer Portal's Target Manager.

Fig. 4. Developed QR code.

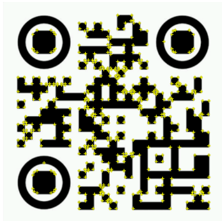

Fig. 5. Pattern image with characteristic points established by Vuforia.

iii) Layer 2 this layer describes the characteristics of the mobile application environment and the incorporation of the animations.

Characteristics of the environment, the implementation of a simple but intuitive interface allows a quick handling and navigation in the mobile application, for which Table 1 shows the icons that were used for the realization of the AR application with their respective description; and 3 main scenes are created: the first scene is presented in fig. 6 and contains the main menu of the application, the second scene allows to visualize the introduction on robotic arms through video and animation, as shown in fig. 7, the third scene allows to perform manual and path control its environment is presented in fig. 8.

Table 1. Icons.

Name	Icon	Action
Introduction		Navigate to the introduction scene.
Control		Navigate to the control scene.
Video		Play video.
Animation		Play animation.
Play		Play the path control.
Graphics		View the trend graphs of the controller.
Return		Return to the previous scene.
Exit		Exit application.

iv) Layer 3 this layer details the advanced control laws that are implemented in the AR application. To meet this objective, the kinematic model of the robotic arm and its respective stability analysis are described.

2.1 Kinematic model

The diagram proposed in fig. 9 shows a robotic arm with generalized coordinates and with a position at the operating end, where h is the position of the operating end in space, l is the length of each link and q is its rotation angle, is given by:

$$\begin{cases} h_x = l_2 C_{q2} C_{q1} + l_3 C_{q2,q3} C_{q1} \\ h_y = l_2 C_{q2} S_{q1} + l_3 C_{q2,q3} S_{q1} \\ h_z = l_2 S_{q2} + l_3 S_{q2,q3} \end{cases}$$

The first-order differential equation is considered (1).

$$\dot{h} = f(h, v, t) \text{ with } h(0)=h_0 \quad (1)$$

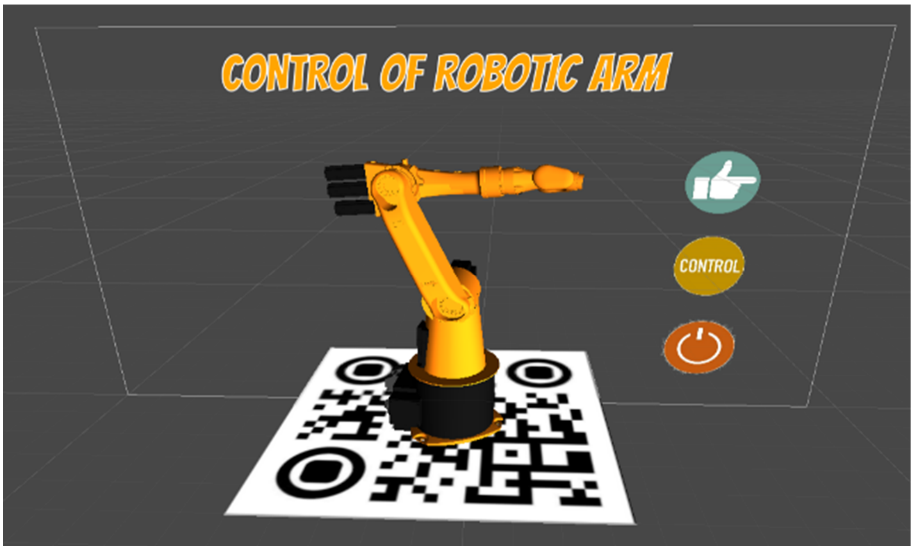

Fig. 6. Main scene environment.

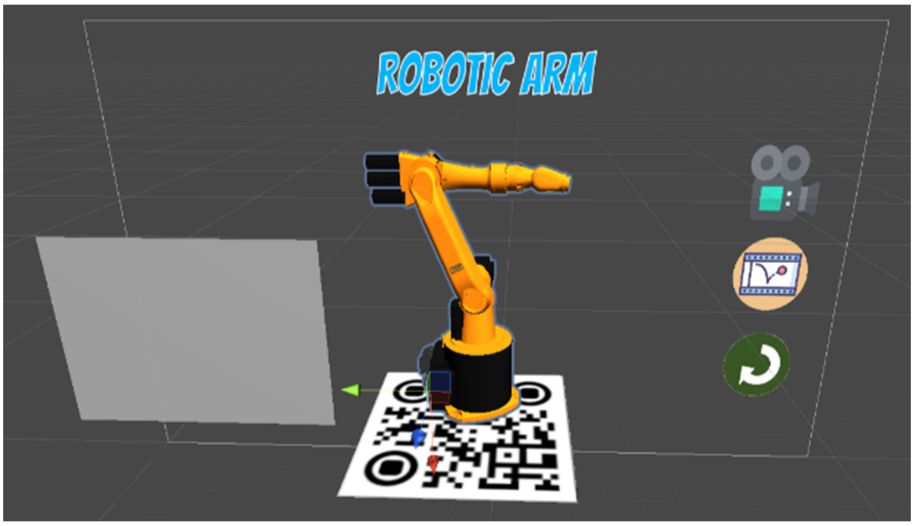

Fig. 7. Introduction scene environment.

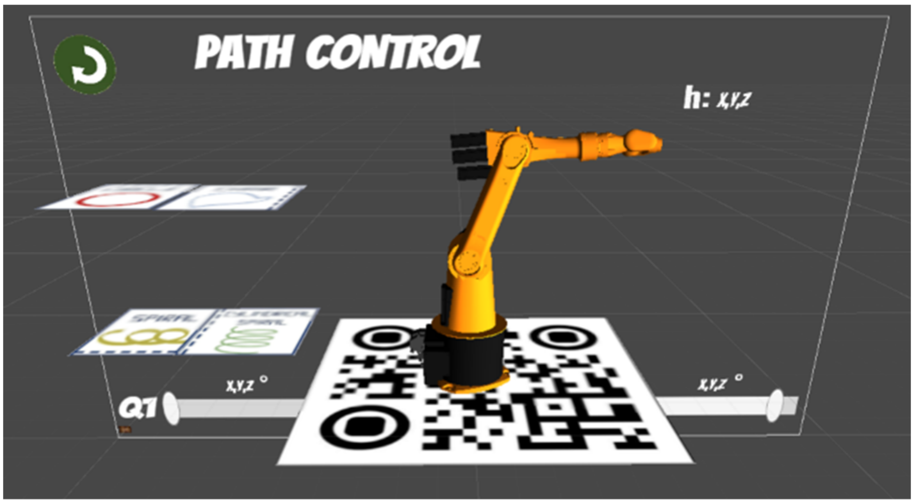

Fig. 8. Scene environment manual and path control.

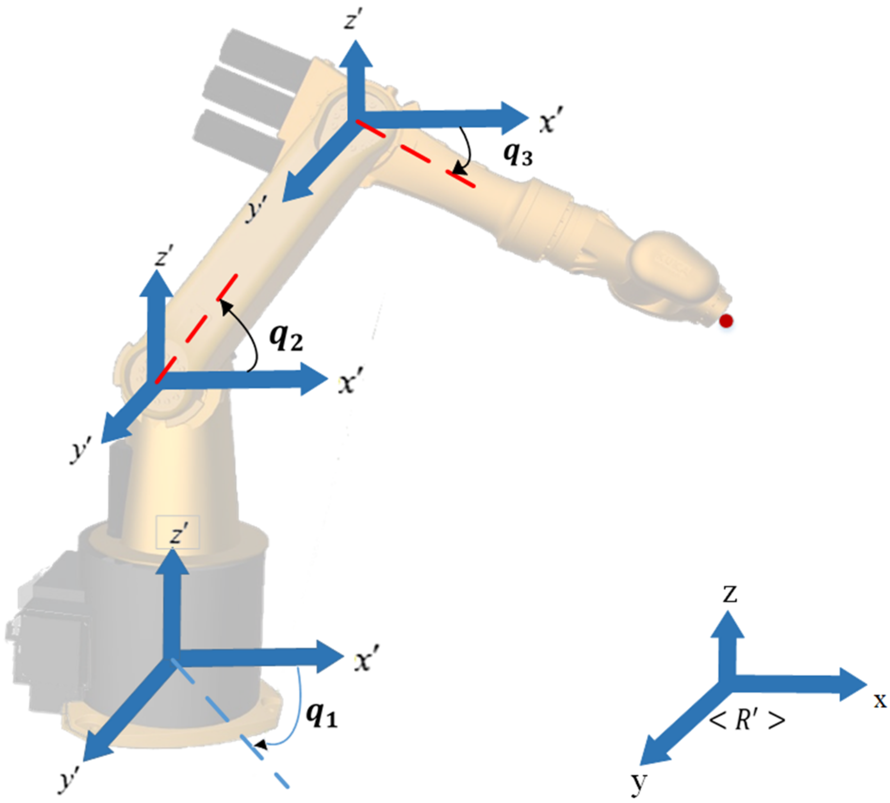

Fig. 9. Robot arm coordinate space.

2.2 Controller

The implemented controller is based on numerical methods given in publication [1], in equation (1) the output of the system to be controlled is represented by h, $\dot{h}$ the first derivative, u the control action, and t the time. The values of $h(t)$ in the discrete time $t = kT_0$, is called $h(k)$ where T_0 represents the sampling time and $k \in \{0, 1, 2, 3, 4, ...\}$.

The use of numerical methods to calculate the evolution of the system is mainly based on the possibility of approximating the state system at the instantaneous moment k+1, if the state and control action over time at the instant k are known, this approach is called Euler's method.

$$h(k+1) = h(k) + T_0 f(h, u, t) \tag{2}$$

Thus, the discrete model can be expressed by

$$h(k+1) = h(k) + T_0 J(q(k))\, v(k) \tag{3}$$

The following expression is used, so that the tracking error tends to zero.

$$h(k+1) = h_d(k) - W(h_d(k) - h(k)) \tag{4}$$

In which, W is the diagonal matrix and its values $0 < \mathrm{diag}(w_{hx}, w_{hy}, w_{hz}) < 1$ are parameters for the proposed controller, h_d is the desired path.

Recital (1) and (2), the system can be rewritten as $Au = b$.

$$\underbrace{J\big(q(k)\big)}_{A}\,\underbrace{v(k)}_{u} = \underbrace{\frac{h_d(k+1) - W\big(h_d(k) - h(k)\big) - h(k)}{T_0}}_{b} \tag{5}$$

Therefore, the viable solution method is to formulate it as a constrained linear optimization problem.

$$\frac{1}{2}\|v\|_2^2 = min$$

v) Layer 4 this layer allows the rotation angles obtained from the sliders as well as from the position and trajectory controls developed, to be incorporated to the links (extremities) of the 3D model in order to generate the respective movement that complies with the trajectory entered by the user.

3 Results obtained

This section shows the augmented reality interface and the usability that it has as a technological tool to manage industrial robots, as well as the simulation of a control algorithm that allows users to follow the desired path. To get started with the app, you need to pre-install the APK on your smartphone.

When the application is run and the QR code is focused, the main scene is shown as shown in fig. 10, to exit the AR application press "exit". Clicking on "introduction" presents a new environment called introduction, pressing the "animation" icon starts the animation of the constituent parts of a robotic arm, as shown in Fig. 11.

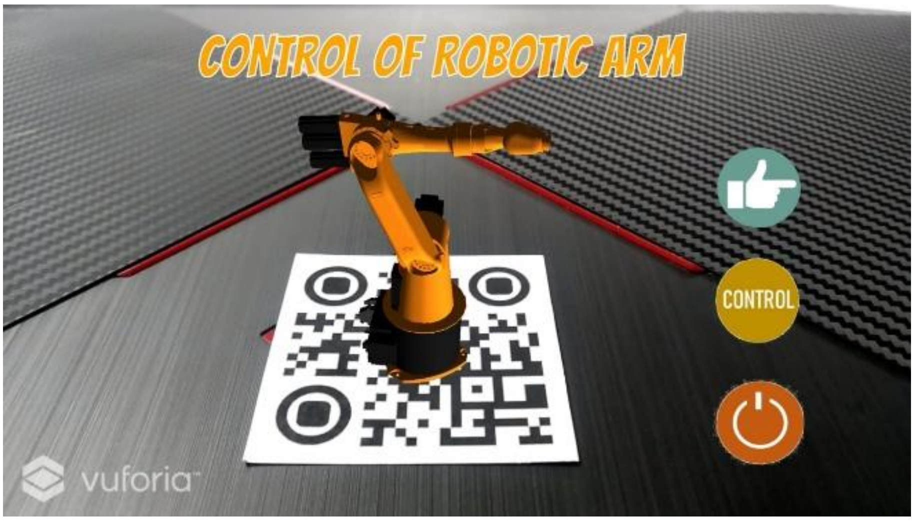

Fig. 10. Main scene of the application when focusing the QR code.

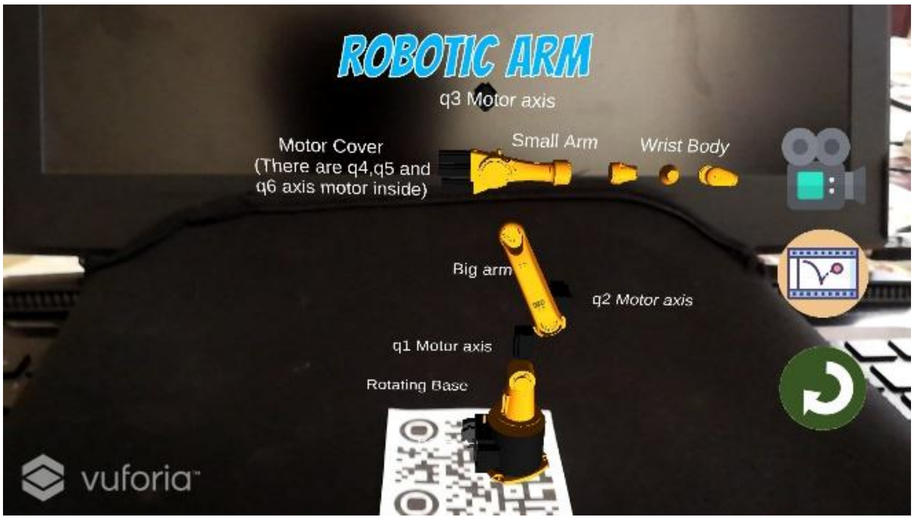

Fig. 11. Animation of robot arm parts.

By clicking on "video" an introductory video is presented containing: general characteristics of a robotic arm, constitution and mathematical modeling, as shown in fig. 12.

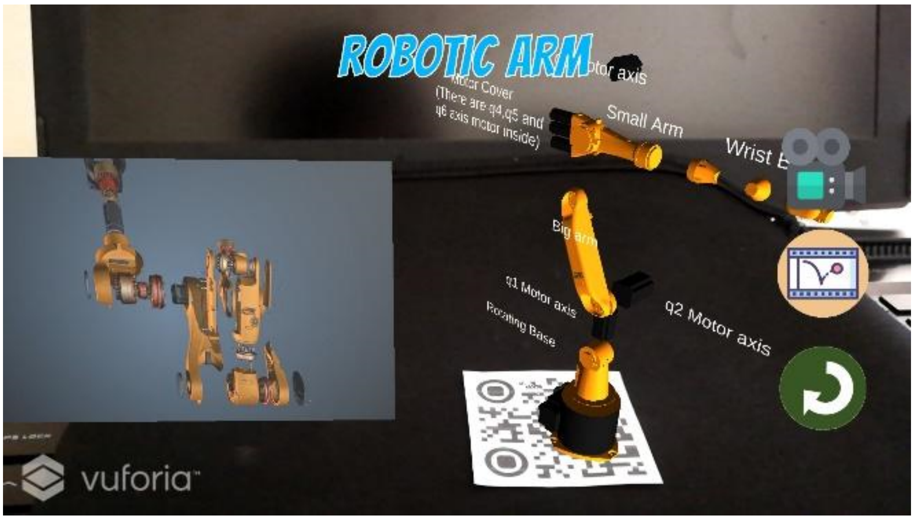

Fig. 12. Video display in AR.

To control the robotic arm, press "control", this shows a scene that contains 3 sliders, as shown in fig. 13, these sliders allow to move the rotation angles of the 3 links, thus performing the manual control, as shown in fig. 14.

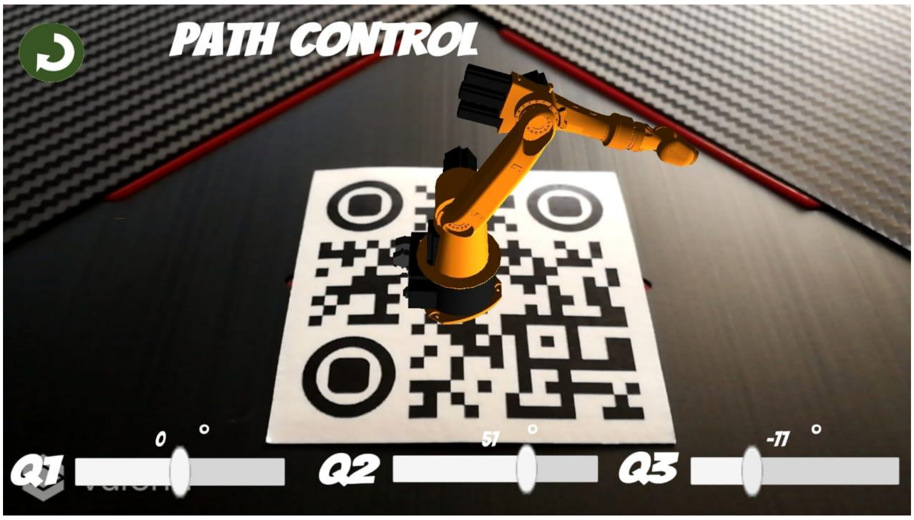

Fig. 13. Robot arm control scene.

For the robot to perform path control it is necessary to focus the path target next to the QR image of the robot arm, when the image is recognized its path appears in 3D, fig. 15 shows the circular path. Clicking on "play" starts the trajectory control in which the operating end of the arm follows the circular trajectory as shown in fig. 16.

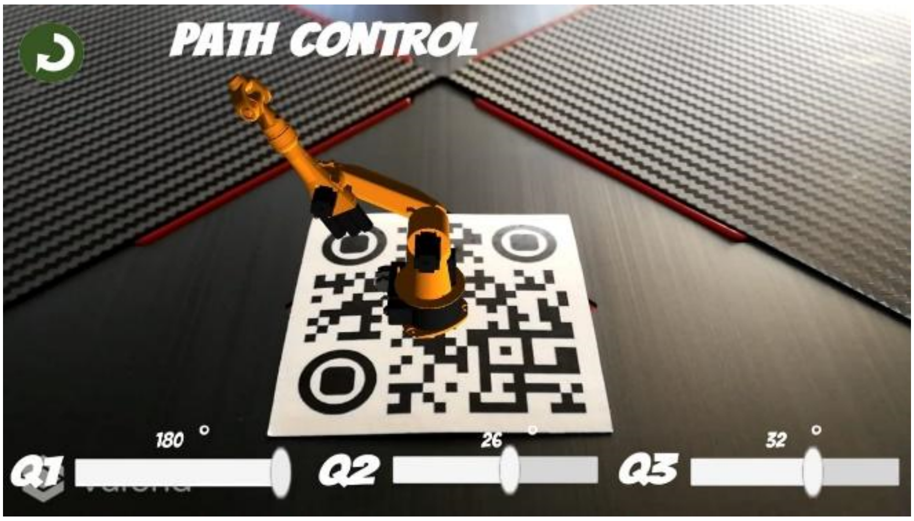

Fig. 14. Manual control of the robot arm when changing parameters q1, q2 and q3.

Fig. 15. Display of the circular path on the robot arm.

The graph of the *x*, *y* and *z* position errors in the AR application as in software Matlab can be seen in fig. 17 and Fig. 18, respectively.

The spiral path of the robot in the AR application can be seen in fig. 19. The fig. 20 and fig. 21 show the graph of the *x*, *y* and *z* position errors in the AR application as in the Matlab under the same conditions respectively.

The cylindrical spiral path of the robot in the AR application can be seen in fig. 22. The fig. 23 and fig. 24 show the graph of the *x*, *y* and *z* position errors in the AR application as in the Matlab under the same conditions respectively.

Fig. 16. Motion of the robot arm on the circular path when applying control.

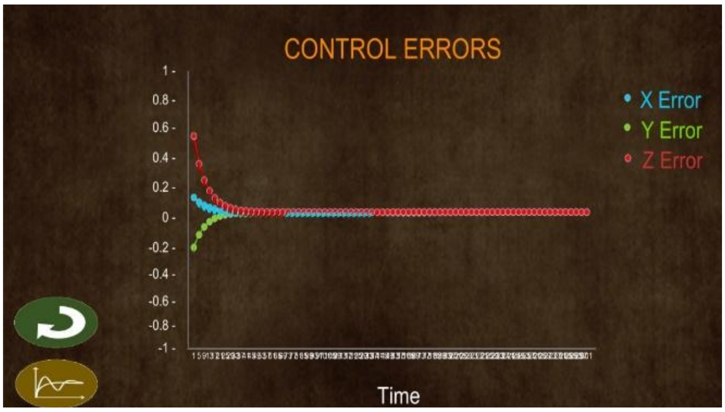

Fig. 17. Position errors *x*, *y* and *z* in the AR application circular path.

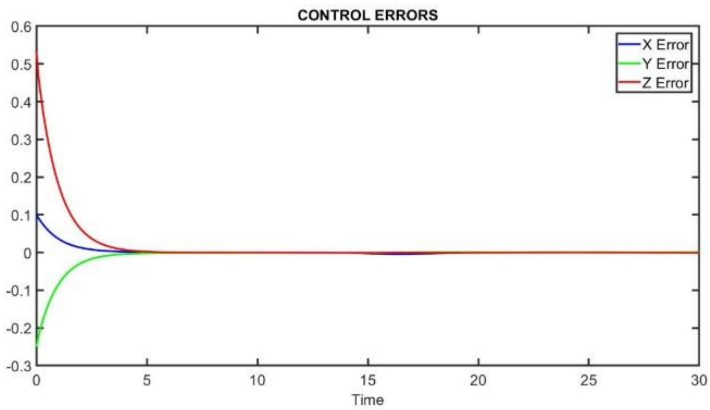

Fig. 18. Position errors *x*, *y* and *z* in Matlab circular path.

Fig. 19. Robot arm movement on the spiral path when applying control.

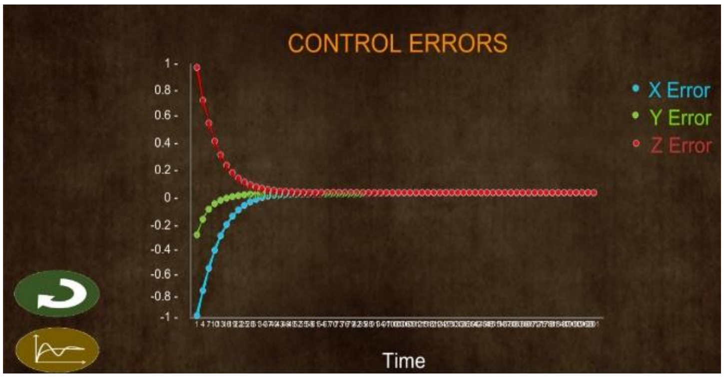

Fig. 20. Position errors *x*, *y* and *z* in the AR application spiral path.

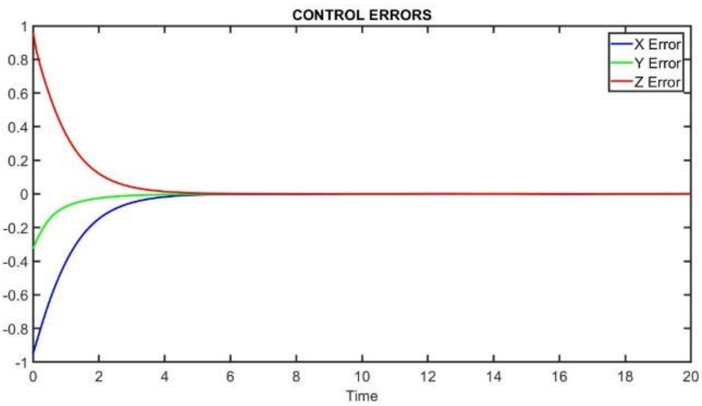

Fig. 21. Position errors *x*, *y* and *z* in Matlab spiral path.

Fig. 22. Motion of the robot arm on the cylindrical spiral path when applying control.

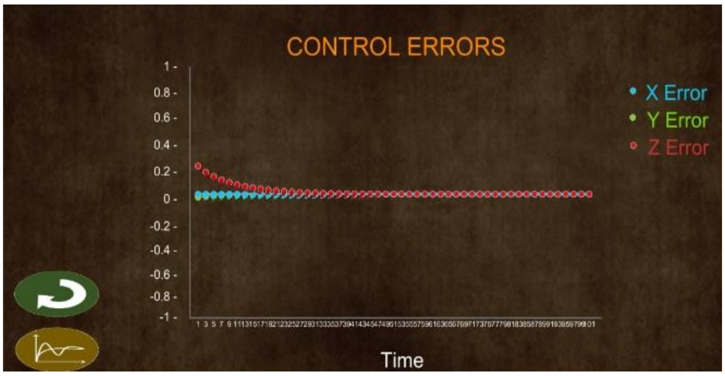

Fig. 23. Position errors *x*, *y* and *z* in the AR application cylindrical spiral path.

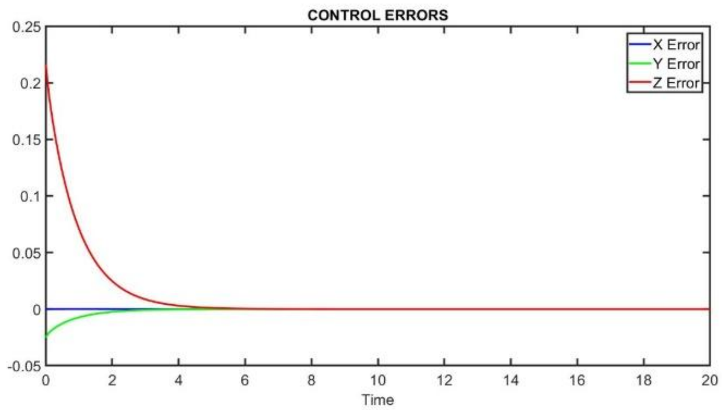

Fig. 24. Position errors *x*, *y* and *z* in Matlab cylindrical spiral path.

Next, the obtained results are shown, that that indicate the validity of the usability of augmented reality, for handling of industrial robots, in a punctual way; in the one of handling and training of industrial robots of three degrees of freedom. The SUS summary evaluation method was used, whose weighting characteristics are described in the document [2]. The sample for the survey is 13 students of the Universidad de las Fuerzas Armadas ESPE of the Electronic Engineering career that are in the last semesters to which a survey of 10 questions was applied according to their experience when using the application. In which it is appreciated in a general way in the scale of styles that generates only a number, the same that represents an average composed by the usability of the application for mobile devices (smartphone), as it is indicated in table 2.

Table 2. Results obtained from the survey.

Questions	Score					Operation
You would like to use the application moderately often				3	10	3.77
Considers that the application is complex and unnecessary	11	2				3.85
The use of the augmented reality application was easy to use				3	10	3.77
You need help or assistance using the application	13					4
The application's functionalities are correctly integrated			2		11	3.69
There is flexibility in using the application			1	2	10	0.31
You think most people would quickly learn to use the application				1	12	3.92
Using the application made it very difficult for him to use	10	2	1			3.69
User interaction was friendly when using the application				3	10	3.77
Considers it necessary to have previous knowledge to use the application	11	2				3.84
TOTAL						34.61

The weighting for the odd questions has a value of 1 to 5, being 1 the worst and 5 the best, while for the even questions, it has a value of 5 to 1, being 1 the best and 5 the worst, these values are multiplied by the number of answers in each question and finally the arithmetic average is obtained. The total obtained, from the sum of the operation of the 10 questions gives as result 34.61; the SUS score is calculated and expressed by means of a multiplication of 2.5 to the total obtained, with which it is determined if the application is feasible for the handling and training of industrial robots, obtaining a percentage of 86.53%, this result represents a high usability for this type of technological tools.

4 Conclusions

The work presents an augmented reality application for smart phones that allows scanning 2D objects and later interacting in the handling of the robotic arm and each of its links, in addition to knowing its parts through animations and multimedia files. Finally, the application allows the visualization of the 3D animation of the robotic arm in the different trajectory control tests established by the user, such as, circular trajectory, spiral and cylindrical spiral, as well as the visualization of the 2D graphics of the control errors, in which it can be seen that the error reaches zero, which indicates that the arm arrives and performs the desired task.

For subsequent works, we will contrast the impact and influence of the application of applied RA in education versus the general teaching methodology, without the implementation of AR technologies; as well as the advantages and disadvantages of learning using this technological tool focused on the assistance and training of industrial robotic arms.

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