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Design and Development of an Augmented Reality Application for Learning a Serial-Link Robot Kinematics

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Abstract: This paper presents an application created using augmented reality (AR) to visualize a serial-link robot according to DH-Parameters. With this technology, the user will be allowed to interact with the three-dimensional virtual object. The application consists of a robot frame assignment and the DH-Parameters tutorial, which are in the form of animation. The visualization of a serial-link robot will be provided to the user in 3D graphics superimposed on the video streaming. For more visualization and immersive, the user can control the three-dimensional virtual robot by an application graphical user interface and AR marker. This research expects that the application can enhance user motivation in robotics learning. So that, the potential of this application is evidenced by the user's survey response.

Keywords: Serial-Link Robot, robot kinematics, augmented reality

1. Introduction

Nowadays, robotics has become an essential technology in the industrial sector and daily human life. Especially in the modern age of industrial 4.0, the robot can be utilized in the production process to enhance productivity, efficiency, and safety for the human operator. Since its' necessity, robotics technology has been included in many colleges and universities' curriculums. However, learning/teaching this subject requires the robot system to help the learner understand clearly. Unfortunately, the cost of the hardware is expensive. Then, several colleges and universities cannot provide an adequate robot system to their students. Furthermore, the traditional teaching/learning media, such as textbooks, contain only text with 2D pictures. So, it is hard for students to get a clear understanding. Researchers utilized various media technology to provide information in the teaching/learning process to overcome these obstacles.

Web-based is a technology which several researchers utilized in their research (Dey & Cheruvu, 2020) (Min, Chien-Pen, Din-Wu, & Shih-Chi, 2008) (Sengupta, Jain, & Kumar, 2013). With this technology, the learner will receive the content in text, 3D/2D computer graphics, and sound from the web application. Moreover, web-based technology provides distance learning and allows the learner to learn at their own pace. Furthermore, computer graphics technology such as virtual reality and augmented reality are outstanding technology in recent. This technology is a tool for converting an abstract concept to a more tangible one and providing an immersive visualization of 3D objects to the user. Virtual reality is a technique that researchers utilized in their works (Bahuguna, Chittawadigi, & Saha, 2013) (Flanders & Kavanagh, 2015) to visualize the robotics concept, such as DH-Parameters, forward kinematics, inverse kinematics, and trajectory planning, etc. This research indicates that using virtual reality can improve students' understanding and self-confidence in the robotics concept.

Moreover, it is easier for the teacher to describe the clear concept to their students using this tool. Augmented reality was utilized in the learning of a four-bar linkage robot kinematics (FayizMaqableh, & Sidhu, 2012) (Frank & Kapila, 2016) to improve visualization and understanding in the learning process. Applying this technology is allowed the learner to visualize the robot model in 3D graphics, which is superimposed on real-time VDO streaming. Furthermore, the augmented reality-based graphical user interface implemented in their research allows users to interact and control the 3D virtual robot. According to the ability of the current technology, this paper proposes the design and development of an augmented reality application applied in the serial-link robot kinematics contents. The research expects that the application will be helpful for both learners and teachers who have not got enough resources. So that, a mobile phone is selected as a deployed device because of its cost and mobility.

2. System design and development

In this research, the system consists of three main modes, which are "Jog" "Tutorial" and "DH-Parameter". The "Jog" mode provides 4 standard robots: Articulate, SCARA, Cylindrical, and Cartesian. To use this mode, the user can take their smartphone, which application already installed with an AR marker. The robot model will be presented to the user via the mobile phone. The user can interact with the model by slider bar, which can move the individual robot joint. The "Tutorial" mode presents the description in 2D text and the animation of the 3D robot that superimposes on the VDO streaming. The concepts of robot kinematics that are provided to the user are robot frame assigning and DH parameters. The last mode is called "DH-Parameter". The user is allowed to create the custom robot configuration. In this mode, the 3D robot will be created according to the DH parameter. To interact with the robot 3D model, the user is allowed to control the individual robot joint by slider bar. Furthermore, they can observe the robot movement in cartesian space using the other marker as a robot target. The system overview is shown in Figure 1.

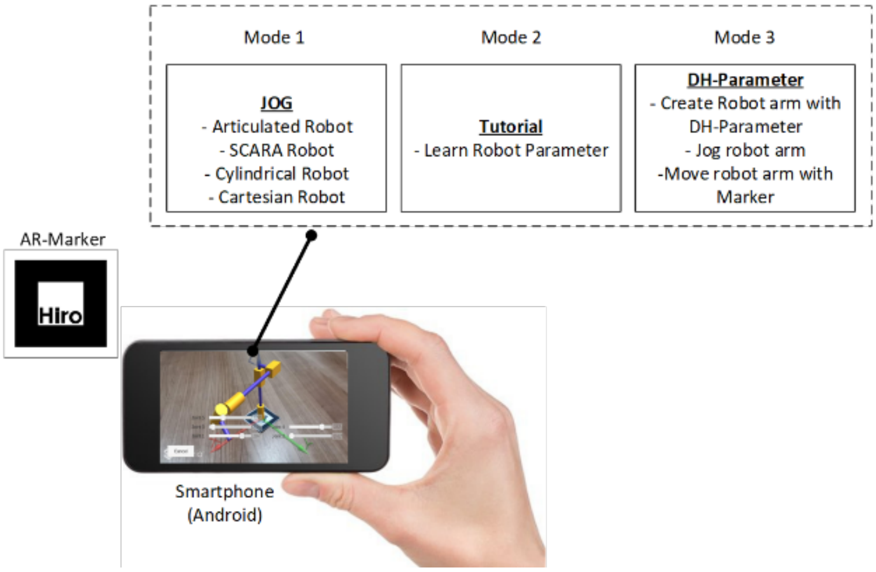

Figure 1. System overview.

2.1 Serial-Link Robot Kinematics

Robot's forward kinematics presents the relationship between joint space and end-effector space in the form of a homogenous transformation matrix. This matrix describes the position and orientation of an interesting frame or a robot end-effector with respect to the base frame when the robot joint variables are given. The coordinate transformations between two frames attached between two links (Kucuk & Bingul, 2014) are computed using the Denavit-Hartenberg convention. This method is utilized to determine four useful parameters for the computation of the forward kinematic, as shown in Figure 2. The first parameter a_i is a distance measure along x_i from the origin of frame {i} to the intersection of x_i and z_{i-1} axes. The θ is the angle between x_{i-1} and x_i axes measure about z_{i-1} axis. Next, d_i is a distance measured along z_{i-1} from the origin of frame {i-1} to the intersection of x_i and z_{i-1} axes. The last parameter is α_i. This parameter is an angle between z_{i-1} and z_i axes that measured about x_i (Spong, 1989).

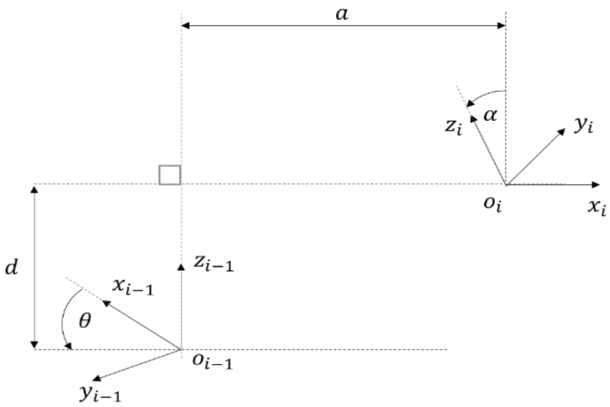

Figure 2. Denavit-Hartenberg Parameters.

The product of four basic transformations produces a general form of the transformation matrix as in (1) and (2).

$$A_i = Rot_{z,\theta_i} Trans_{z,d_i} Trans_{x,a_i} Rot_{x,\alpha_i} \tag{1}$$

$$A_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\alpha_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The method for determining the robot joint variables when the end-effector position and orientation are given is called inverse kinematics. There are several ways to solve this problem, such as geometric, numerical, or machine learning methods. For example, Figure 3 presents an example of determining the inverse kinematics with the geometric method for the 3 DOF robot.

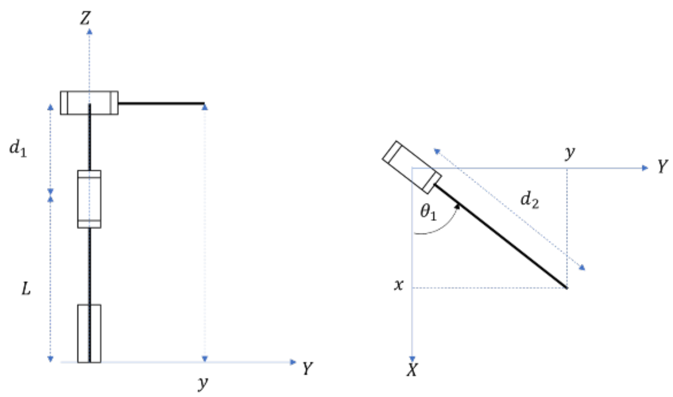

Figure 3. The left picture is a projection of robot configuration on the y-z plane (Side view). The right picture is a projection of the robot configuration on the x-y plane (Top view).

The left picture of Figure 3 presents the side view of this robot configuration. So that d_1 can be determined from (3)

$$d_1 = z - L \tag{3}$$

where

z is the end-effector position in the z-axis

L	is the distance between joint 1 and joint 2

On the other hand, d_2 *and* θ_1 can be determined from the left side picture of fig.3 as shown in (4) – (6)

$$d_2 = \sqrt{x^2 + y^2} \quad (4)$$

$$\tan\theta_1 = \frac{y}{x} \quad (5)$$

$$\therefore \theta_1 = tan^{-1}(\frac{y}{x}) \quad (6)$$

As mentioned before, there are several methods to solve the inverse kinematics problem. For complex robot geometry, closed-form inverse kinematics solutions become challenging. In addition, each robot needs a unique computation. Inverse kinematics for any generic robot arm can be solved via mathematical optimization. As a result, we must resolve the optimization issue. An objective function $g(q)$ is shown in (7) with constraint (8). The objective function, which is an error between the desired pose of the end-effector and a current position from its forward kinematics function will be minimized.

$$\min g(q) = \| x_d - f(q)\| \quad (7)$$

constraint

$$q_{min} < q < q_{max} \quad (8)$$

where

q	is robot joint variables
x_d	is a desired pose of the robot end-effector
$f(q)$	is forward kinematics function

From the forward kinematics, the homogenous transformation which describes the relationship between robot joint variables and its end-effector pose can be written in (9).

$$x = f(q) \quad (9)$$

This paper applies an optimization method called gradient descent to determine the robot joint variables when the end-effector pose is given.

Gradient

$$\nabla f(q) = \frac{f(q+\Delta x) - f(q)}{\Delta x} \quad (10)$$

Update variable

$$q_{i+1} = q_i - \alpha\nabla f(q_i) \quad (11)$$

where

x	is a current position from its forward kinematics function
α	is a learning rate
i	is an iteration

2.2 Augmented Reality Robot Application

The AR-Robot application has been developed using Unity3D games engine with Vuforia SDK. Blender software is used for 3D robot rendering. In the software, there are two main modules which are illustrated in fig.4. After obtaining the robot's joint angles from the GUI, the forward kinematics module calculates the robot end-effector pose according to the inputted angles. Subsequently, a 3D model of the interested robot will be imported and rendered superimpose on the VDO streaming using an augmented reality technique. For the inverse kinematics module, the desired end-effector pose can be sent to this module through direct input from the application GUI or a marker pose. This module solves the inverse kinematics problem with two approaches. The close-form solution method is used when the application is in the "Jog" mode. For the "DH Parameter" mode, an arbitrary 3D robot will be generated. The optimization method is selected to solve this problem. After the inverse kinematics module determines the joint variables, the results will be sent to the forward kinematics module. Then, the 3D graphics will be rendered on the video streaming as shown in Figure 4.

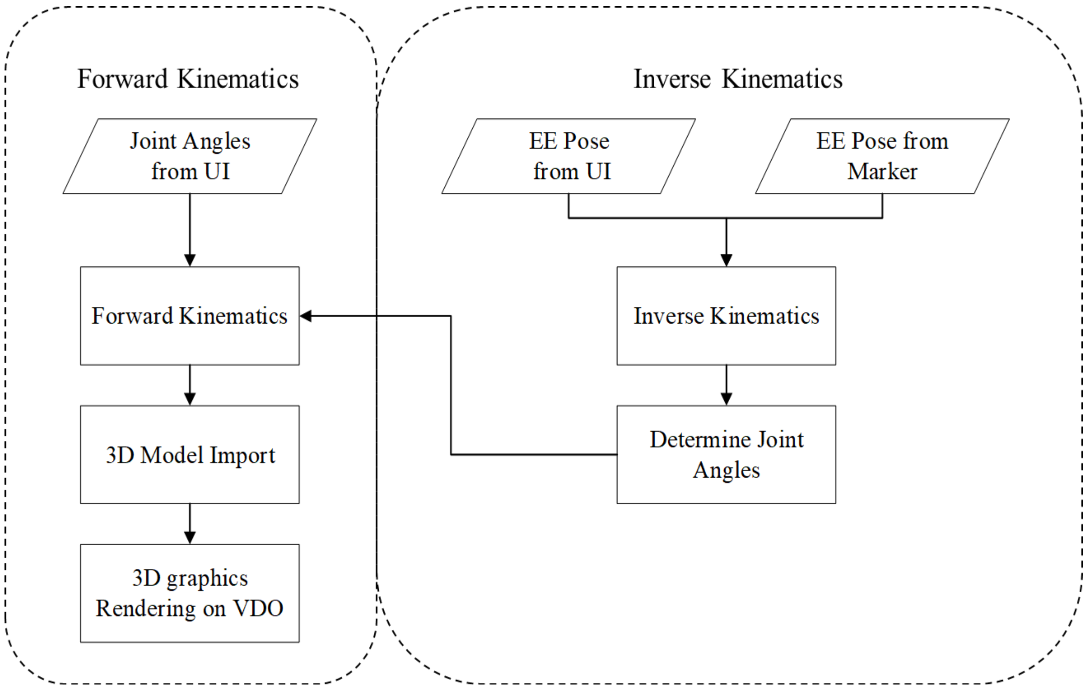

Figure 4. Main modules of AR-Robot application.

The implemented application consists of three main menus which are "Jog", "Tutorial" and "DH-Parameter" as Figure 5. For the "Tutorial" menu, the application provides the tutorial of assigning coordinate frames and extracting DH-parameters of a robot manipulator. The student/user can input the robot joint variables to the selected robot model and observe the result of the forward kinematics in "Jog" mode. Moreover, in the "DH-Parameter" mode, the student/user is allowed to insert their robot DH-Parameter. They can observe the result of forward and inverse kinematics of their robot in the form of 3D graphics which is superimposed on the VDO streaming.

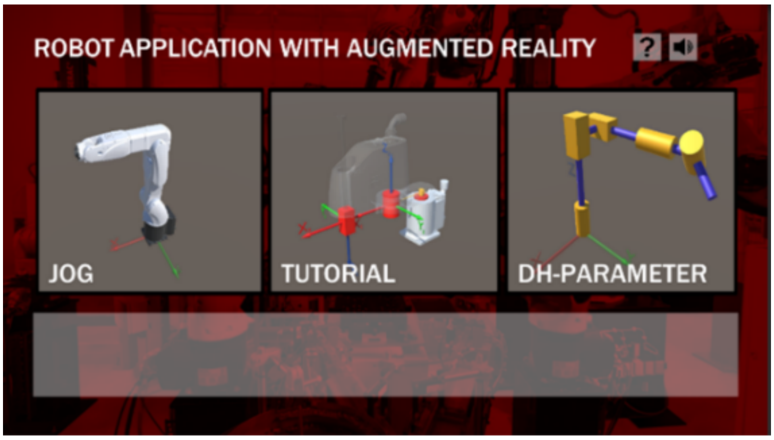

Figure 5. Robot Application with Augmented reality Main Menu.

In the “Tutorial” mode, there are four robot types (Articulated, SCARA, Cylindrical, and Cartesian) that the user is allowed to select. The 3D robot, its coordinate frames, DH-parameter, and the descriptions of each step will be presented on the screen in Figure 6. This part of the application is helpful for the user/student who does not have prior knowledge of robotics.

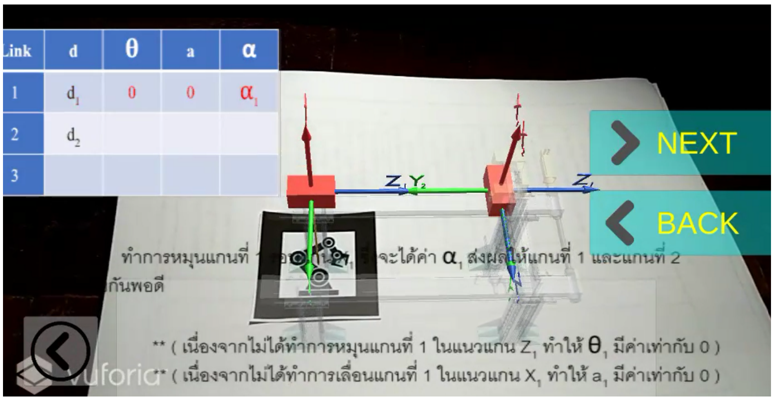

Figure 6. Tutorial Mode.

Figure 7 presents the scene of “Jog” mode. In this mode, the 3D model of the selected industrial robot will be presented. The user/student is allowed to control the robot by sliding the slider bar to change the robot joint variables and observe the result of its forward kinematics.

Figure 7. Jog Mode.

For the “DH-Parameter” mode, the user/student can input the DH-parameter and select the robot joint type (Revolute or Prismatic) on the application screen as Figure 8.

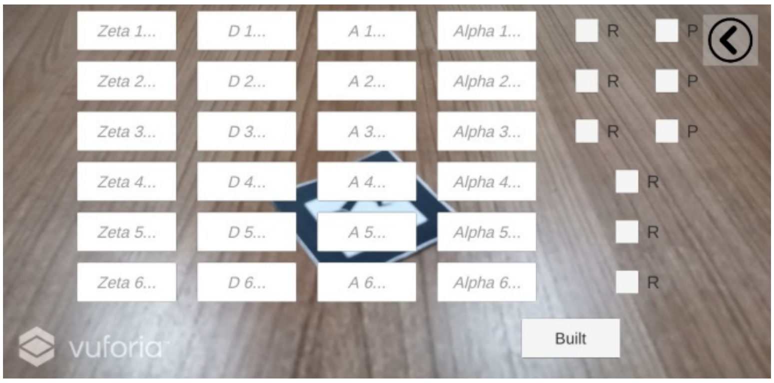

Figure 8. DH-Parameter Mode.

After the "Built" button is pressed, the 3D robot model will be generated and presented on the screen as Figure 9. The user can observe the robot forward kinematics by the input value of the robot joint variables through slider-bar as Figure 10. To visualize the result of the generated robot's inverse kinematics, the user is allowed to input the target pose on the screen or use the other marker as a target for the robot as Figure 11.

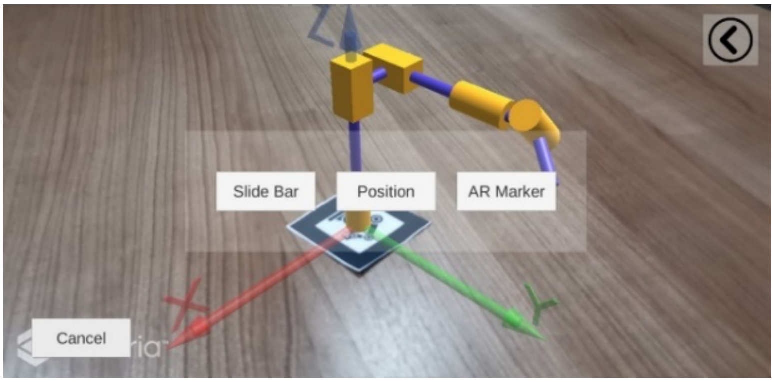

Figure 9. The generated robot according to the input DH-Parameter.

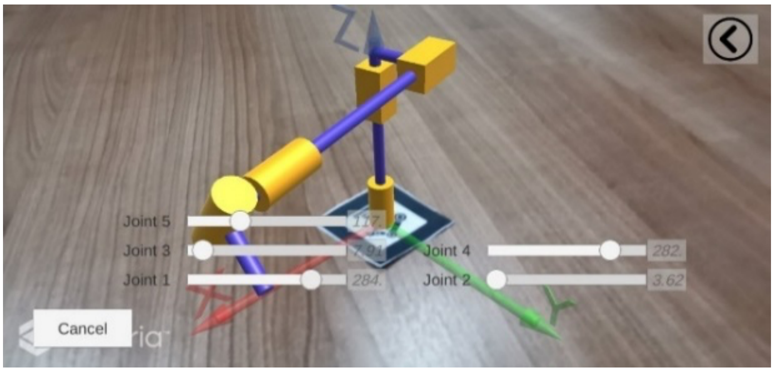

Figure 10. Control robot via sliderbar.

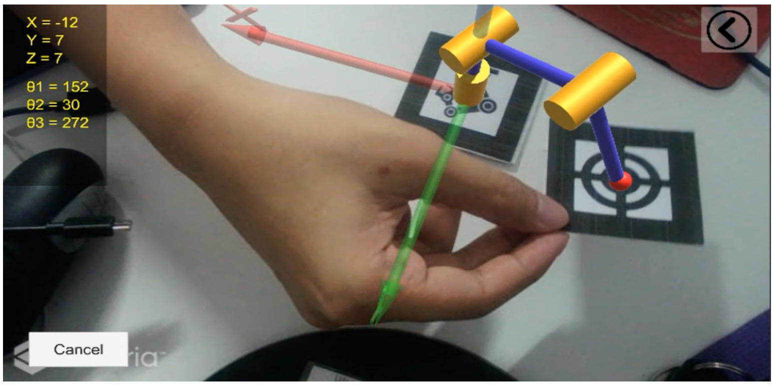

Figure 11. Inverse kinematics result.

3. Experimental Setup and Results

To investigate the performance of this application, the inverse kinematics calculation time and its position accuracy were evaluated. The experiment was set up on two different devices. The first device is a desktop computer with Intel Core I7-6700HQ, VGA GTX950M, and 4GB memory. The other is a mobile phone with android EMUI 9.1, CPU Kirin 980 Octa-Core, and 8GB memory. The robot model utilized in the experiment is articulated, SCARA, cylindrical and cartesian robot. Moreover, the custom robot configuration will be utilized in the experiment. The results demonstrate that an average position error and an inverse kinematics calculation time when testing with standard robot configuration on a desktop computer are ± 4 units and 16.5 ms, respectively. For testing an arbitrary robot configuration on the desktop computer, it is found that an average position error is ± 1 unit with more than 200 ms of an inverse kinematics calculation time. The experimental results, which are test on the mobile phone, indicate that the average position for the standard robot is± 3.75 units with 25 ms of an inverse kinematics calculation time. Running the arbitrary robot simulation takes more than 1 sec of inverse kinematics calculation time with ± 1 unit position error.

Furthermore, the efficacy of this application on enhancing student motivation and satisfaction in robotics learning was evaluated using a questionnaire, which is a quantitative method. Before applying this method to the research evaluation, Item-Objective Congruence (IOC) was utilized to assess the items of this questionnaire. The implemented questionnaire obtained 0.72 of an IOC average score from three experts in education and engineering. The evaluation data is collected after the users, who are mechatronics engineering students of the Faculty of Technical Education, learned the robotics concepts through this application. The participants of this study were separated into two groups. The students with prior knowledge in robotics concepts are the first group. The second group is students who did not learn this subject. All participants were asked to learn the robotics concept via the implemented application at their own pace. Afterward, their opinion on enhancing motivation and satisfaction in robotics learning were collected with a questionnaire. The results indicated that the average enhancing motivation and satisfaction scores are 4.1 and 4.2, respectively, with a Likert scale.

4. Conclusion and Future Works

The traditional robotics teaching media like a textbook is difficult for the student to understand the robotics concept. So that they need the robot system to visualize and demonstrate the abstract content which are robot frame assignment, DH-parameter, robot kinematics or dynamics, etc. Nevertheless, the real robot system is costly for several institutes. To overcome this obstacle, an augmented reality application for robot visualization was developed because of its visualization ability. This application can provide the basic concept of robotics to the user and present the visualization of a 3D robot. Moreover, to enhance the user's learning interest and motivation, the user is allowed to interact with the 3D robot through the application GUI or the other AR marker. The result demonstrated that this application with augmented reality is suitable for teaching/learning the basic concept of robotics and enhancing the motivation in robotics learning. For future works, the robot dynamics module should be developed with a more natural user interface.

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