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Learning planar robotics with an open source online laboratory ⋆

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Abstract: This work describes two open source and low-cost online laboratories to explore the field of planar robotics and the tools used to create them. Each lab contains two versions: a simulation lab and a remote lab, both ready-to-use within an online course or available to be built by the students. Additionally, the reduced cost of the remote lab allows students to make it at home as a classical hands-on system. This last do-it-yourself approach provides them the means to gain experiential knowledge and perform tasks related with control, electronics, robotics and programming.

Keywords: Planar Robots, Remote Laboratories, Virtual Laboratories

1. INTRODUCTION

In recent years a multitude of robotics courses have been offered in almost all the scientific areas and for all ages, and wherever it is offered, it draws the attention of the students Fabregas et al. (2016); Gil et al. (2014); Neamtu et al. (2011); Chaos et al. (2013); Jara et al. (2011); Goldberg and Siegwart (2002). These courses go from practical scenarios to pure theoretical issues, comprising many different learning goals. Traditionally, face-to-face robotics courses focus in first place on the theoretical concepts, and in second place, on the practical experience. Both parts are needed inside the learning process to acquire a complete education in robotics, therefore, the equilibrium between both results in a better understanding of the subject. But reaching this equilibrium is a big challenge for teachers because of the interdisciplinary nature of robotics subjects.

A new student of robotics can be easily overwhelmed because of the amount of areas mixed together: sensors and actuators theory, programming, control theory, machine vision, transformations, forward and inverse kinematics, electronics, pattern recognition, path-planning, neural networks, etc. Then, include all this knowledge in just one course and ask students to learn it may be an impossible task. The teacher which needs to address this problem usually combines lectures with animations, videos, simulations and labs, and commonly it helps to fix the new concepts. For example, lets imagine this set of experiences that enclose numerous full courses from a fundamental grasp of the nature of planar robotics to a global insight of the construction of a basic planar robot:

- *Kinematics*: The labs are presented to the students to be used in two versions: 1) as a simulation or 2) accessing to the real hardware remotely. In these labs they can move the joints or select where the final effector must be placed (direct and inverse kinematics).
- *Sensors and actuators*: The pieces of the robot can be provided to the students to build the skeleton of a certain planar robot. Using a not fixed structure for the robot, each student can obtain different configurations, then different robots. The student may then explore the available sensors and actuators and code some elements of software to do the data acquisition and processing.
- *Mathematical simulations*: The simulated labs are given to the students, and to which they must change the application to, for example, add capabilities or explore different control algorithms.
- *Robot design*: The students must design not only the structure of the robot but also the software to control the system. To do that, they will use a specification sheet, that describes the systems and details the structural characteristics, the available sensors and actuators.

These experiences use real or simulated robots, that present many advantages when creating resources compatible with lectures. However, is not always possible to work with a wide variety of robots because of their availability and price.

In this article, we present two labs, each dedicated to one robotic architecture, and developed in two versions: simulation and remote. First, a set of two simulations made with Javascript and HMTL5. Second, a set of two remote labs made using a re-configurable and 3D-printable kit. All the hardware and software elements are open source and

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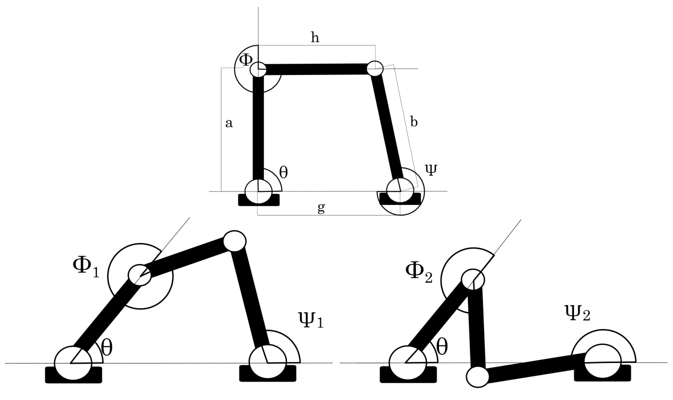


Fig. 1. Visual representation of the two solutions behavior which is shown in equation 1

are based on low cost technologies. These characteristics make the labs fast to re-design and compatible with lectures. Then, these labs allow the teachers to use them in many different ways and cover all the example approaches presented before.

The rest of the document is as follows. Section 2 describes the two labs presented in this work. Section 3 presents the software tool Easy Java/Javascript Simulations (EJsS) that helps teachers and students in the creation of the labs, and finally Section 4 gives the conclusions and some future lines of work.

2. LABS DESCRIPTION

This work presents two laboratories targeted at initiation courses in planar robots, a subgroup of robots which contains planar constraints that limit their movements inside a fixed plane.

In particular, we focus on two planar robots that have been deeply studied in the robotics area McCarthy and Soh (2011); Robson and McCarthy (2005); Liu and Wang (2003); Ruth and McCarthy (1999); Merlet et al. (1998); Gosselin and Angeles (1990), namely:

- One DOF planar robot with four rotational joints (4R). It is called the *4R linkage*. The 4R linkage is a closed chain of joints, which has two fixed pivots as shown in Figure 2. The arm distances are fixed, as the system contains only rotational joints. The mathematical model can be obtained using common kinematics analysis McCarthy and Soh (2011). The system can be modified to include the Two DOFs planar robot with five rotational joints (5R) Feng et al. (1996), that is shown in Figure 3.
- A planar manipulator with a variable number of DOFs (NR). This robot architecture does not use a closed chain of joints, and the basic model is a 2 DOFs with two joints. The arm distances are fixed, as the system contains only rotational joints. The mathematical model can be obtained using common kinematics analysis Kormushev et al. (2015); Kormushev et al. (2015); Zakia et al. (2019).

For each robot, we have developed a simulation and a remote lab, which are based on a model of the robot and on a remotely operated robot, respectively.

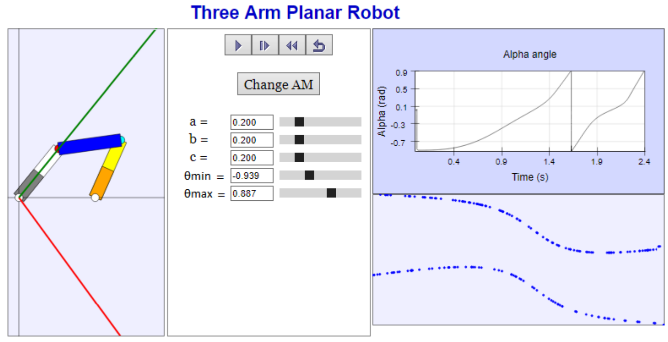


Fig. 2. HTML5 applications of the 4R planar robot simulations.

2.1 Simulation labs

Usually, a robot presents a fixed design where the geometrical parameters, as the length of the arms, can not be easily modified. A simulation, on the contrary, does not have that limitation. We can make the virtual robots as flexible and re-configurable as we need, to allow the user to explore different configurations. On the one hand, we consider ideal robots inside a Cartesian plane, without flexing arms or loose joints. On the other hand, their movements can be restricted by simulated architectural constraints and by developers-defined restrictions, like maximum/minimum joint angles.

The 4R simulated lab is based on the analysis of the geometry of closed loop structures. The geometry of this structure uses as origin the joint with angle labeled as θ in Figure 1. Considering that the 4R linkage is a 1DOF system, one of the rotational joints is controlled by an actuator, and can be defined as the input of the system. For controlling purposes it is considered that θ is the input angle and Ψ the is output angle, that are represented in Figure 1.

The analysis of the mathematical relationships between these angles leads to equation 1.

$$\Psi(\theta) = arctan\left(\frac{B}{A}\right) \pm arccos\left(\frac{C}{\sqrt{A^2+B^2}}\right) \qquad (1)$$

Where A, B and C are relationships between the input angle θ and the length of the arms:

$$A(\theta) = 2abcos(\theta) - 2gb \qquad (2)$$

$$B(\theta) = 2absin(\theta) \qquad (3)$$

$$C(\theta) = g^2 + b^2 + a^2 - h^2 - 2agcos(\theta) \qquad (4)$$

Two solutions are obtained from the presented equation and returns two values of θ. Each θ value correspond to a

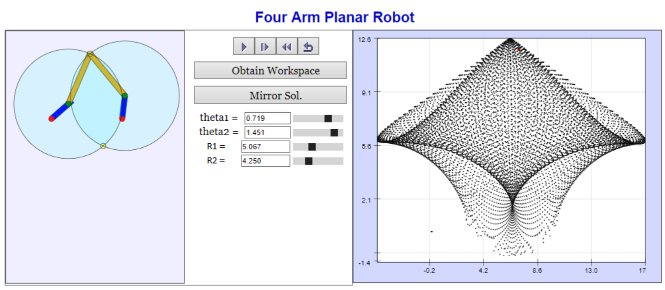


Fig. 3. HTML5 applications of the 5R planar robot simulations.

different position of the planar robot, as is seen in Figure 1.

The geometric relationships between the angles in the planar robot impose certain limitations to the available configuration. In general terms, these constraints are expressed in the form of conditions that restrict the values of A, B and C. The analysis of the 4R planar robot leads to the following restriction in Equation 1:

$$A^2 + B^2 - C^2 \geq 0 \quad (5)$$

This constraint must be satisfied or the linkage cannot be assembled. In this regard, the limits of the angles are defined by the solution given when the restriction is equal to zero. The solutions return the maximum and minimum θ angles, and therefore the range of the input θ angle. In the same way, the limits over the output Φ angle can be calculated, returning the output range. With the restrictions given and the solutions obtained it is possible to define the workspace for the planar robot over the input and the output.

Figure 2 shows the HTML5 applications of the 4R linkage simulation, that is given to the student to learn the basis of the planar robots. This simulation, allows to define the length of the arms, the distance between the fixed point and to include some additional restrictions. The HTML5 applications presents also the workspace along with the output and input angles when the input angle is changed. However, the flexibility is enhanced by including the possibility of developing new features. Depending on the teaching goals, the student may use the software tools that are available to include:

- Other available approaches to obtain the two solutions and workspace that has been presented.
- To design a new controller to control the angle for a given reference.
- The code to solve the inverse kinematic problem when the user gives an input to the simulation.

The students can also work with the 5R linkage simulation that is based also on the analysis of the geometry of the closed loop structure. The geometry of this robot is shown in Figure 4, and now uses two inputs for the two rotational joints. The geometrical analysis and solutions available to obtain the workspace are multiple in the bibliography Feng et al. (1996); Cervantes-Sánchez et al. (2001).

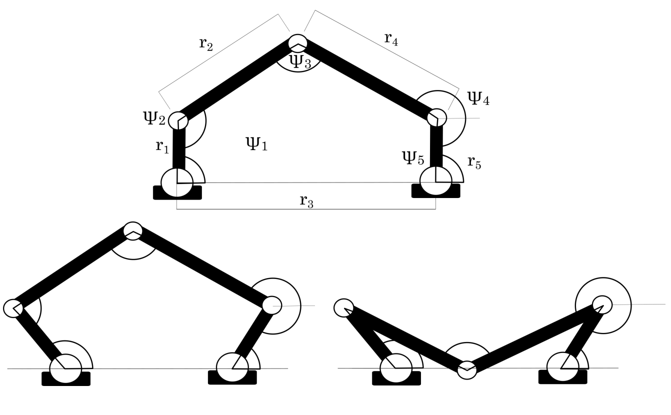


Fig. 4. Visual representation of the 5R linkage robot with the two solutions that can be obtained for the same input parameters.

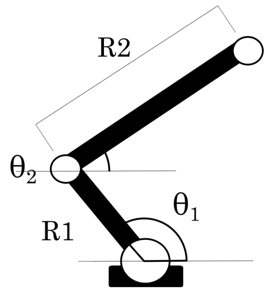


Fig. 5. Visual representation of the 2R planar Robot.

The NR lab is the second simulated planar robot. The idea behind the NR lab is a planar robot with N arms in an open chain. However, this work presents only the 2R open chain planar robot, as an educational example. This robot is built with two arms and two rotational joints that can be controlled using the input signals of each joint.

Figure 5 shows a visual representation of the 2R planar robot that is used in the simulation. These kind of systems have been used frequently in the bibliography Arya et al. (2016). The position of the final effector (X_c, Y_c) depends on the joint angles and it is obtained using only mathematical rotations:

$$X_c = R_1 cos(\theta_1) + R_2 cos(\theta_2)$$
$$Y_c = R_1 sin(\theta_1) + R_2 sin(\theta_2)$$

The system is simple enough to solve the inverse kinematics problem using just the geometric approach, Rout and Mittal (2008); Mahil and Al-Durra (2016):

$$\theta_1 = tan^{-1}\left(\frac{Y_c(R_1 + R_2 cos(\theta_2)) - X_c R_2 sin(\theta_2)}{X_c(R_1 + R_2 cos(\theta_2)) + Y_c R_2 sin(\theta_2)}\right)$$
$$\theta_2 = cos^{-1}\left(\frac{X_c^2 + Y_c^2 - R_1^2 - R_2^2}{2R_1 R_2}\right)$$

To explore other control problems it is possible to use the direct positions of the end effector to analyze the dynamics of the system. The process is done by differentiating θ_1 and θ_2, that lead to a system of equations 9 Rout and Mittal (2008); Zakia et al. (2019). These equations express the dynamic model of the planar robot using τ_1 and τ_2 that represent the torques, θ_1 and θ_2 the angles of the joints and m_1 and m_2 the masses of the arms.

$$\dot{\theta}_1 = \frac{\dot{x} cos(\theta_1 + \theta_2) + \dot{y} sin(\theta_1 + \theta_2)}{R_1 sin(\theta_2)} \quad (6)$$

$$\dot{\theta}_2 = -\frac{\dot{x}x + \dot{y}y}{R_1 R_2 sin(\theta_2)} \quad (7)$$

$$\ddot{\theta}_1 = \frac{bc - ae}{ad - b^2} \qquad \ddot{\theta}_2 = \frac{bc - ae}{ad - b^2} \quad (8)$$

$$(9)$$

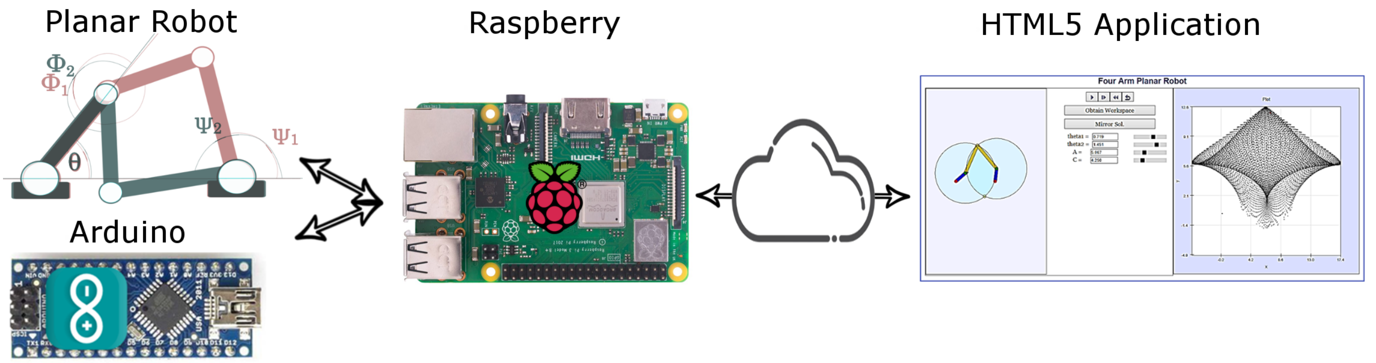


Fig. 6. Global architecture of the remote laboratory of the planar robot.

$$
\begin{aligned}
a &= (\frac{m_1}{3} + m_2)R_1^2 + \frac{1}{3}m_2R_2^2 + m_2R_1R_2cos(\theta_2)\\
b &= m_2(\frac{R_2^2}{3} + \frac{1}{2}R_1R_2cos(\theta_2)\\
c &= (\frac{m_1}{2} + m_2)gR_1cos(\theta_1) + \frac{m_2}{2}gR_2cos(\theta_1+\theta_2)-\\
&\quad m_2R_1R_2sin(\theta_2)\dot{\theta}_2\dot{\theta}_2 - \frac{m_2}{2}R_1R_2sin(\theta_2)\dot{\theta}_2^2 - \tau_1\\
d &= \frac{m_2}{3}R_2^2\\
e &= \frac{m_2}{2}R_1R_2sin(\theta_2)^2 + \frac{m_2}{2}gR_2cos(\theta_1+\theta_2) - \tau_2
\end{aligned}
\tag{10}
$$

These equations lead to a non-linear control system whose equations can be simplified to a linear system, Zakia et al. (2019). Both, the non-linear and linear system, may be used in control education labs, closing the loop over any of the available physical variables, such as joint angles, torques or the position.

2.2 Remote lab

Remote labs are adaptations of real equipment connected to the actuator circuits that allow interaction through the Internet, as remotely operated systems. The two labs are controlled using HTML5 applications with interactive elements, following the same architecture used in literature, because of their known advantages Chacón et al. (2013); Guinaldo et al. (2013); de la Torre et al. (2011).

The set of planar robots are composed by two separated parts. On the one hand, the server side, which contains: 1) The hardware of the planar robot and 2) the devices to enable the communications capabilities. On the other hand, the client side is the HTML5 application.

The main difference between simulation and remote labs is the server side, as it must access to the hardware. One of the efforts of the presented work has been focused in the use of open standards and technologies to reduce the economical cost:

- The server tasks are carried out by a development platform: the *Raspberry Pi* single board computer. The Raspberry Pi board offers many interesting capabilities such as as *USB* client and host, *Ethernet*, *HDMI*, *GPIO* with *PWM* and even built-in support for *I2C*.
- An Arduino Nano board, which is in charge of the acquisition tasks. Figure 6 shows the main architecture of the server side, where the Arduino and the Raspberry Pi exchange data using serial communication.
- The planar robot arms were designed using CAD tools and are made using a 3D printer. The pieces used to build each arm are shown in Figure 7 in a 3D representation. This modular design allows to build many different robot configurations, where each joint can be equipped with a motor and a position sensor.

The internal operating system inside the *Raspberry Pi* board is a *Raspbian Linux* distro, that is commonly used is these boards and allows to develop our server side in multiple programming languages. The server provides the lab functionality as a set of services that are available to the client-side application. It is responsible of tasks that include the following:

- *Serial Communication*: The *Raspberry Pi* board communicates via USB with the Arduino Nano board. The Arduino board performs the data acquisition and provides an API to interface with the sensors and actuators, which are connected to the on-board Analog/Digital and Digital/Analog converters. It runs two threads, to:
  - Read the raw value of the sensors, that is a value proportional to the measuring of the resistance, and
  - Change the signal that feeds the actuators, the motors of the joints.
- *Control*: The controller processes the measurements received from the sensors, and change the status of

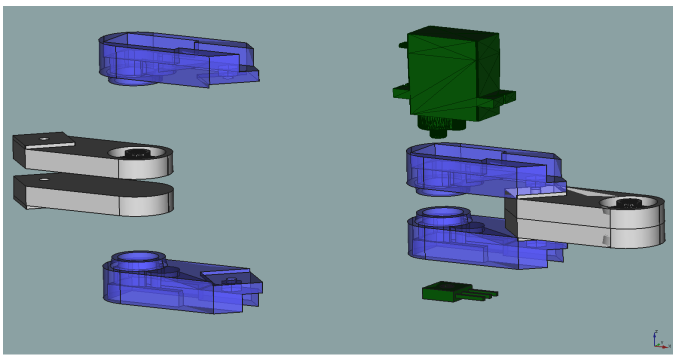
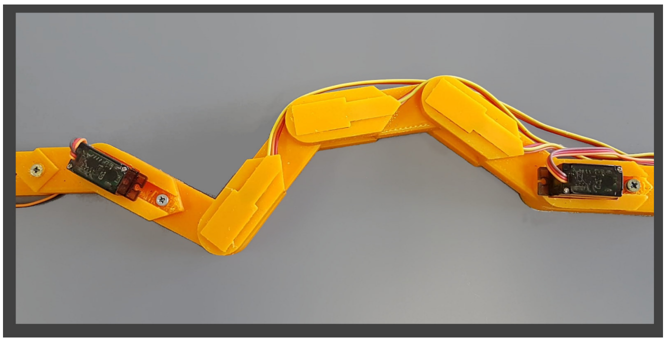
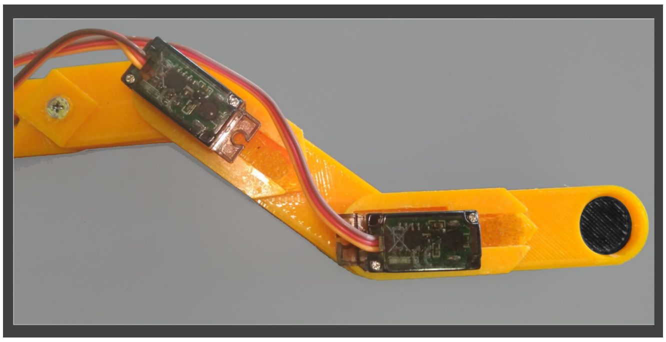


Fig. 7. 3D pieces in a CAD application, these are designed to hold a motor or servo and a potentiometer in each joint.



(a) 4R and 5R planar closed loop robots



(b) 2DOF planar robot remote system

Fig. 8. Two remote experimental setups of planar robots, 4R/5R linkage and the NR planar robot.

the actuators, to maintain the value of the controlled variable at set point. By default, this task uses a PI controller to control the angular position of the movable joints.

- *Network communication*: Implements the server capabilities needed to exchange data with the client and it is listening for incoming user connections. The communication is based on Websockets protocol and JSON data format, that are well known and available in the main Web browsers.

Two remote experimental setups have been developed and complement the simulations presented. Figure 2 shows both, the 4R/5R linkage and the NR planar robot.

The first one is the 4R/5R, Figure 2.a), and it is a combined system because it can be configured to behave as:

- The 5R linkage, as a 2DOFs system, allows to control the signal of two joints. As a closed chain, the opposite ends are fixed to the table. In this lab, by default, the user can change the angle of the two actuators manually and obtain readings from the sensors of all the joints. For each new angle all the values of the sensors are gathered in order to draw the workspace point-by-point. The lab also is prepared to solve the inverse kinematics problem and to obtain the input angles for a certain point in the workspace.
- The 4R linkage, is enabled if one of the motors is configured to fix its angle in the same position. It means that one of the joints is fixed, leaving the system with four rotational joints. In this situation, the system is just 1DOF planar robot and is possible to obtain the workspace or work with the inverse kinematics, as in the 5R linkage.

The second one is the 2R open chain, Figure 2.b), the final effector is represented by a black dot in the end of the last arm. In this lab, the angles of each joint are controllable manually to solve the direct kinematic problem, but, is also possible to move the final effector to certain point in the workspace solving the inverse kinematics problems.

3. EASY JAVA/JAVASCRIPT SIMULATIONS

The online labs presented in this work are made using Easy Java/JavaScript Simulations, that is a well known tool to develop simulations and remote labs in STEM areas Besada-Portas et al. (2013); Gil et al. (2014); Vargas et al. (2009); Farias et al. (2010); Dormido et al. (2007); Chacón et al. (2013). EjsS is a open-source tool developed in Java that assists non-expert programmers in the creation of dynamic simulations. The tool was originally designed to be used for learning purposes, and relies on a model-controller-view architecture to ease the design process of the virtual or remote lab. An user can neglect the implementation details and focus on the science and knowledge behind the idea, writing equations, coding the behavior and/or the visual interface. The motivation of this approach is to enlighten the creation process to teachers. They may or may not have advanced knowledge of programming, but that are proficient in their topics and can benefit from the incorporation of digital tools into their courses.

As some of the exercises presented are intended to be performed by students with a basic programming skill, this software is suitable to learn and improve this capabilities in a learning-by-doing approach. The students may use this tool for different purposes depending on the skills and knowledge. For example: to improve their programming skills, to enhance the capabilities of the simulations (e.g. including more arms or changing the constraints) or even to enhance the remote lab experience.

4. CONCLUSIONS AND FUTURE WORK

This work has presented a collection of simulation and remote labs for robotics education. The available types of robots can be used to solve direct and inverse kinematics problems involved in the movement of robots. The simulations use a mathematical tool, EjsS, that is adequate to develop the labs. One of the goals of using EjsS is that it can be used by students to improve their programming skills in the robotics area. These planar robots labs give a flexible system to test the limits and behaviors of many different configurations due to the use of open and low cost technologies and simulation tools. Therefore, the labs are not restricted to the samples contained in this work and more complex lab experiences can be designed, for example:

- Other available approaches to obtain the final effector positions and the workspace.
- A new controller to control:
    - · The output angle for a given reference.
    - · The torque of a given joint.
    - · The position of the final effector.

- The code to solve inverse kinematic problem when the user gives an input to the simulation.
- Augmented reality or machine vision to enhance the experience with the labs.

It is also planned to consider new experiments for advanced students, that are also possible, but are not developed yet. However, the combination of open and low cost platforms give a wide range of possible labs. Future work will consider to test the lab in robotics courses and to analyze the data from these educational experiences to obtain valuable information from student and teachers.

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