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Development and Evaluation of Remote Virtual Teach Pendant for Industrial Robotics Education*

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In industrial robotics education, students often do not have sufficient opportunities to practice skills such as robot programming due to large class sizes, limited lab time, and the cost of robots. There is an urgent need for engineers with industrial robot knowledge and programming as part of their skill set. A teach pendant is a commonly used and inexpensive method of programming industrial robots. This paper describes the development and evaluation of a virtual teach pendant and web server that enables students to do lab exercises remotely. It has been used to help students become familiar with robot anatomy, practice robot motion planning, and program a robot remotely to complete a simple pick-and-place assembly task. The system has been evaluated by 19 two-year college students, 159 four-year college students, and 150 high school students. Pre and post-testing and survey results suggest that the system is useful for learning robot anatomy, motion planning, and robot programming; students would like to have more tools like this to help them learn; and the interface is user-friendly and easy to manipulate. Future directions may include adding advanced programming functions (such as conditional and loop structures) and providing haptic feedback.

Keywords: robotics; robot programming; teach pendant; remote operation

1. Introduction

1.1 Benefits of virtual and remote laboratories

Laboratory experiences play a critical role in science education [1]. Hands-on experimentation with physical systems is essential to helping students learn. However, systems such as industrial robots can be expensive. When class sizes are large, individual students often do not get adequate hands-on experience. With the emergence of the Internet during the 1990s, concepts such as simulated physical systems (Virtual Lab) and remote experimentation using real systems (Remote Lab) have become more popular [1]. Heradio et al. conducted a comprehensive literature of virtual and remote laboratory development work up to 2015. They noted that hands-on, virtual and remote lab experiences can be combined to address space, cost, and maintenance issues faced by engineering and science educators and to enhance active learning experiences [2]. For example, Kolb’s constructivist cycle for enabling high order experiential learning could be implemented by (i) using virtual labs in preparatory sessions; (ii) utilizing hands-on labs in interactive lectures that involve experimentation; and finally (iii) using remote labs to support students’ repetitive experimentation [2, 3].

1.2 Trends in robotics education

Castellanos et al. designed a remote lab to allow users to modify trajectories and change control parameters of a robot manipulator as well as to design and test their own control algorithms using Matlab and Simulink tools [4]. Their laboratory has been used successfully in undergraduate courses on control theory and in graduate courses in robotics and advanced control. The lab is shared by Universidad Central ‘Marta Abreu’ de las Villas, Universidad de Cienfuegos in Cuba, and Instituto TecnoloÂgico de MinatitlaÂn in Mexico.

Torres describes the development and evaluation of a RoboLab system that contains virtual simulation tools and an interface for remote access to Scorbot ER-IX and PA-10 robots [5]. Students first complete exercises within the simulated virtual environment. After verifying the results, they can then execute the actions using the real system via tele-operation. Students can practice basic concepts related to robotics, kinematics, and trajectory design using RoboLab. The RoboLab system was evaluated by students enrolled in a Robots and Sensory Systems course. Students completed the course lab assignments either during their hours of practical lessons, or remotely from any other location. The evaluation found that although students were happy to accept a virtual laboratory that allowed a flexible timetable for their experiments, the majority preferred to have a real laboratory at the university so that they could work together with their classmates. Students also considered teacher support to be essential. On the other hand, the response to remote access to robots was also positive and interesting to students, because the remote robots made practice more attractive and real, in comparison to simulation.

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Alimisi reviews the current situation in the field of educational robotics and identifies new challenges and trends [6]. He suggests that (1) curriculum is the key to improve student learning, not robot technology alone; (2) teachers and educators should provide multiple pathways into robotics and to engage young people with diverse interests and learning styles; and (3) developing a vibrant and active community in educational robotics will promote further networking of researchers, teachers and learners.

1.3 Robot programming

Robots have become significantly more powerful and intelligent with time, and are moving into more service-oriented roles. Biggs and MacDonald have noted that with more widespread use, there is a need for easier-to-use and more flexible programming systems. In their review of manual and automatic programming systems, they note that manual systems require the user/programmer to create the robot program directly, by hand, while automatic systems generate a robot program as a result of interaction between the robot and the human [7]. Lozano-Perez reviews requirements for and developments in robot programming systems, focusing on the areas of sensing, world modeling, motion specification, flow of control, and programming support [8]. Billard describes a common method for programming of robots—Robot Programming by Demonstration, also known as imitation learning [9]. Nicolescu and Mataric discuss natural methods for robot programming, including instructive demonstrations, generalization over multiple demonstrations and practice trials [10].

In the area of industrial robots, Pan et al. provide a comprehensive review of recent research on programming methods for industrial robots, including online programming, offline programming, and programming using Augmented Reality (AR) [11]. Wang et al. propose an optimized path planning method for off-line programming of an industrial robot [12]. Sang Choi et al. present a lead-through method and device for industrial robots, which they found to be more efficient and intuitive for discrete point or continuous-path robot programs [13]. Maeda and Nakamura propose view-based teaching/playback as new method for robot programming [14]. This method aims to achieve greater robustness against changes of task conditions than conventional teaching/playback without losing general versatility. The method is composed of two parts: teaching phase and playback phase. The method was implemented and tested in a virtual environment with a limited sequence control robot. Zaeh and Vogl present a method for intuitive and efficient programming of industrial robots based on Augmented Reality [15]. Tool trajectories and target coordinates are interactively visualized and manipulated in the robot's environment by means of laser projection. Zieliński provides an object-oriented approach for robot programming [16]. Freund et al. discuss a process-oriented approach to efficient off-line programming of industrial robots, presenting two approaches: automatic trajectory generation and tech-in/playback programming using virtual reality techniques [17].

In industry, the most widely used method for robot programming is by using teach pendants [18]. A user uses the pendant to guide a robot along the path of completing a desired task. At the same time, at different points along the path, coordinates are recorded. After the task is complete, the recorded points can be played back at a slower speed to verify the accuracy of the program. An active focus of research is the development of soft teaching pendants as an alternative to traditional hardware teach pendant devices. Soft teaching pendants are potentially useful not only for industry applications, but also for robotics and industrial automation education. In educational institutions, due to equipment availability and lab time limitations, students often do not have sufficient opportunities for hands-on learning. Having the ability to remotely program a robot outside of scheduled lab times can allow more students the opportunity to gain experience using a teach pendant.

Kaluarachchi et al. present a soft pendant for a 6-axis Yaskawa Motoman HP3J robot [19]. Abbas et al. present the idea of an augmented reality-based teaching pendant using a smart phone [20]. Jan et al. propose a smartphone-based control architecture for a teaching pendant, providing a user-friendly interactive control input method to the robot's operator [21]. However, the user interface design is rudimentary and does not resemble an actual teach pendant; also, it is not clear if the robot position is recordable.

1.4 Motivation

To realize the benefits of remote laboratories, build on trends in robotics education, and mirror robot programming methods used in industry, this paper describes the development and evaluation of a Virtual Teach Pendant for a LabVolt 5150 Robot. The layout of the graphical user interface (GUI) is the same as an industry teach pendant while also providing the flexibility of remote control using a computer or a mobile device. A playback feature is included, allowing the user to record and play back the steps used to teach the robot. The virtual teach pendant allows increased access to equipment, facilitates self-paced learning, and provides the opportunity to experience remote control of a robot system. In addition, findings and lessons learned from evaluations of the system by high school students, two-year college students, and four-year college students are presented.

2. Development

Fig. 1 provides an overview of the system. After logging in, the user can press symbols representing each joint of the robot (Fig. 2). Based on these

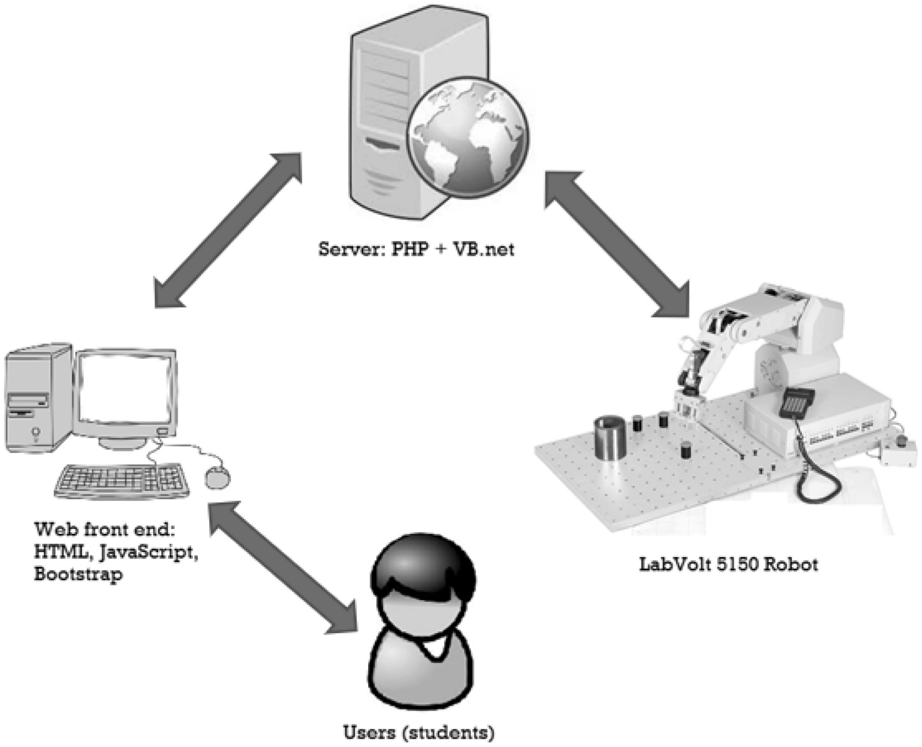
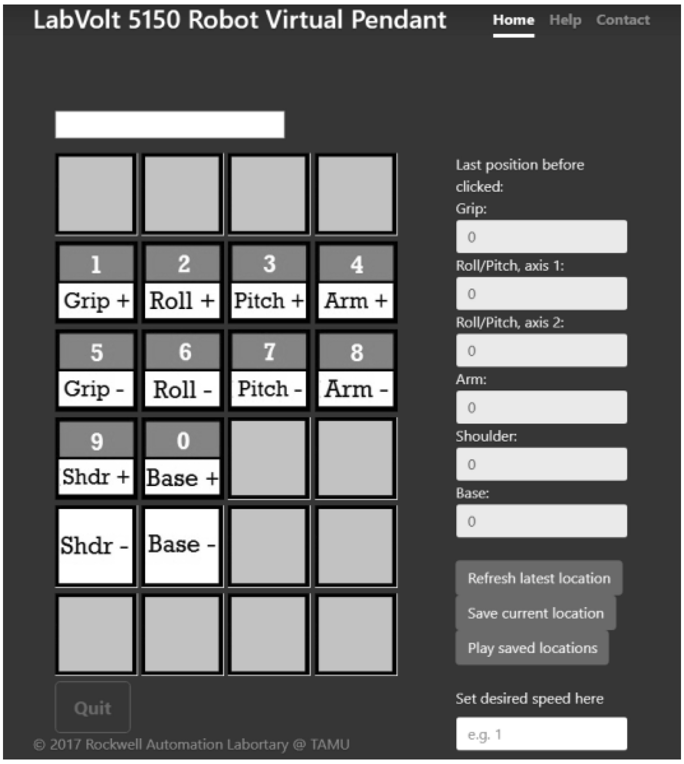


Fig. 1. Overview of Virtual Teach Pendant system.



Last position before clicked:

Grip: 0

Roll/Pitch, axis 1: 0

Roll/Pitch, axis 2: 0

Arm: 0

Shoulder: 0

Base: 0

Set desired speed here: e.g. 1

Fig. 2. Virtual Teach Pendant user interface.

inputs, a series of coordinates are sent to a robot controller, which moves the robot to the corresponding locations (point-to-point programming). The user can monitor the movements of the robot through a webcam or IP cam.

3. Process flowchart

The LabVolt 5150 Robot Virtual Teach Pendant system consists of the following components: web UI (user login system + main function), background executable file, and the robot. Fig. 3 illustrates a typical user interaction with the LabVolt 5150 robot through the system.

4. Design diagram

In order to communicate with the robot through a web UI, two main components are required: a web application, developed using a mix of JavaScript, CSS, HTML and PHP, and a background executable file, which is written in Visual Basic. The web application displays all available options and saves users' selections into a text file. The background executable file (also known as the actual control unit) runs simultaneously and in parallel with the web application. It monitors user inputs and sends instructions to the robot as soon as it captures changes from the user input file. The LabVolt 5150 comes with a Dynamic Link Library (DLL) to allow external programs to communicate with the robot. Currently, the robot takes one input at a time. Once the robot moves, the background program records the relative coordinates and saves them to a coordinate file for display to the user. The diagram below (Fig. 4) illustrates the dynamic

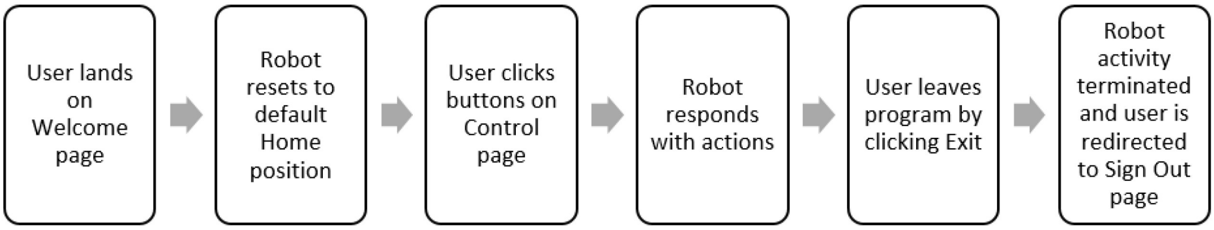


Fig. 3. Process flowchart describing user interaction with system.

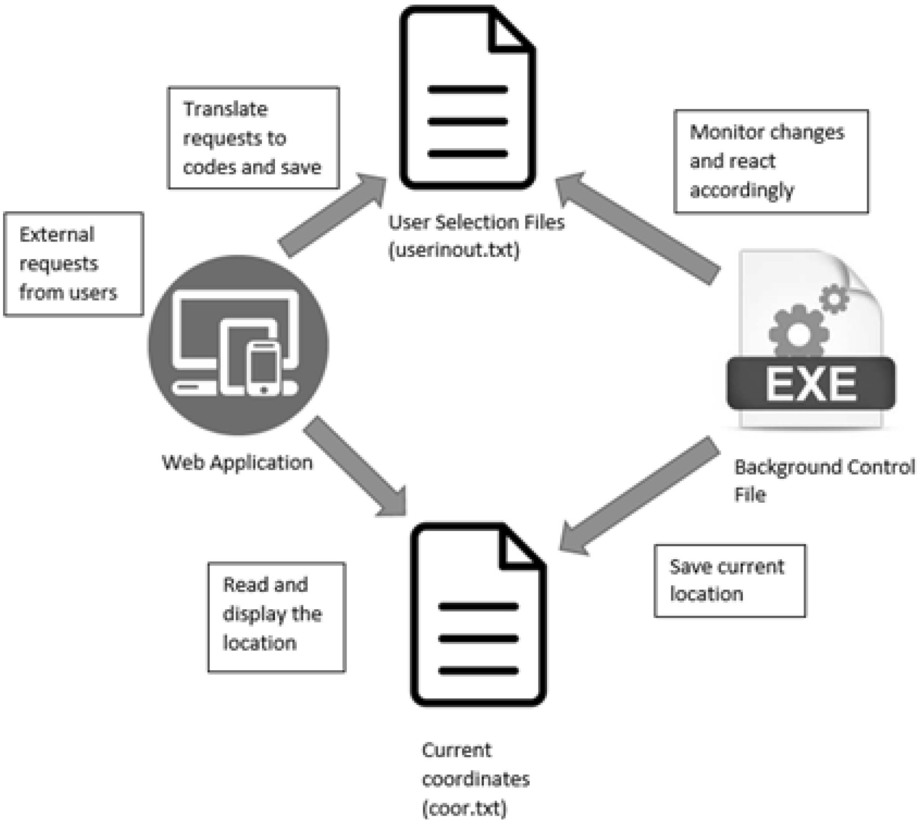


Fig. 4. Illustration of relationship between system components.

between the web application and the background control unit.

5. System layout

Fig. 5 is a screenshot of the web page from the user's perspective. The left half of the image shows camera views of the robot from different angles. The top-left camera presents the front view of the robot; the top-right camera projects the side view of the robot; and the bottom left camera presents top view of the robot. On the right half of the image is the Virtual Teach Pendant interface. The Virtual Teach Pendant is used to control each joint of the robot and thereby move the robot to a desired location within its travel path to accomplish a task.

6. Evaluation

The Virtual Teach Pendant has been evaluated by 19 two-year college students, 159 four-year college students, and 150 high school students. The goals were to determine:

- Did the VTP help students to learn about basic robot anatomy, links and joints, and how to use the pendant to move the robot.
- Student opinions about various aspects of the VTP, such as did it help them learn about robot programming, is it relevant to their education, is the user interface easy to understand, and do they want more tools like it.
- Student comments. Students provided ratings and comments using an opinion survey. In addition, the two and four-year college students completed a pre- and post-test.

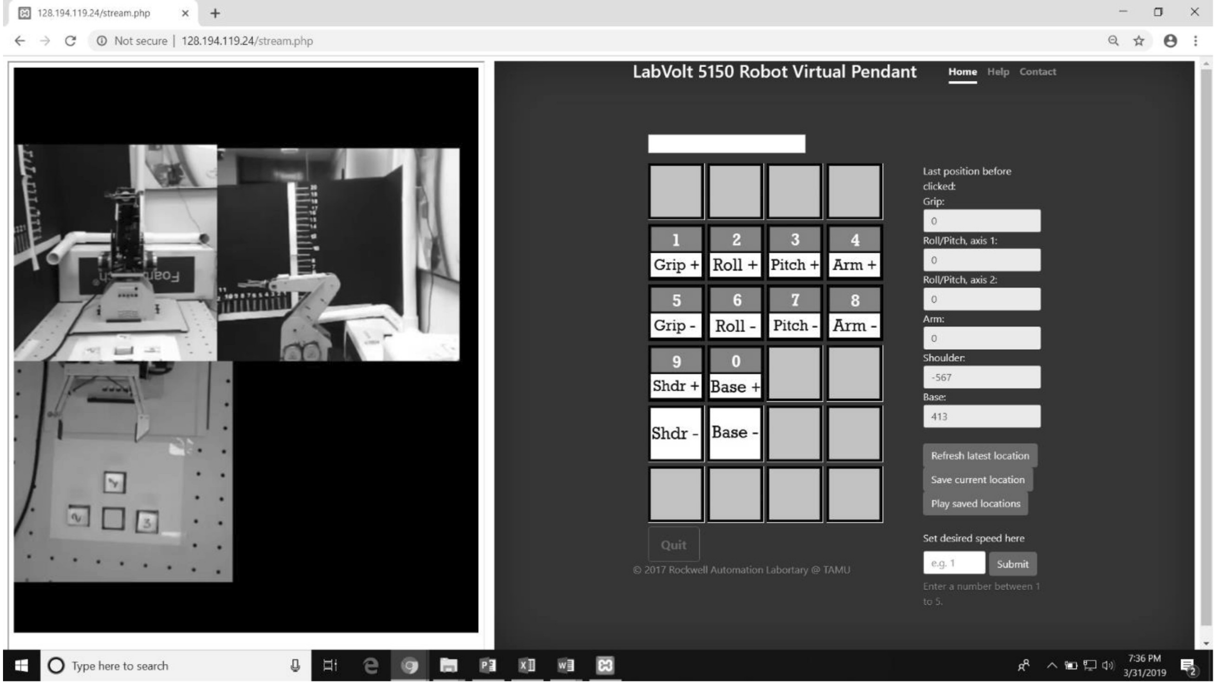
6.1 Evaluation by two-year college students

Participants. Participants in the pre- and post-testing were 19 two-year college students enrolled in an Industrial Automation and Robotics course, during a lab session in which they were learning how to program a robot to accomplish a pick and place task.

Materials. Students' knowledge of articulated robot anatomy, manipulating robots, and programming a robot using a virtual teaching pendant (VTP) was assessed. Fig. 6 shows sample test questions:

Lab exercises. Students used the VTP for two lab exercises. For the first lab exercise, the task was to move four plastic blocks through a maze without touching the sides of the maze or dropping the blocks. For the second lab exercise, the task was to move three ping-pong balls (ordnance) to a disposal container. Fig. 7 shows the layout of the maze, the robot starting and end points, the sides of maze, and the layout of the ordinance and disposal container.

Pre and post-test data analysis and results. The pre and post test data were analyzed to see if there was statistically significant score improvement between tests. Two stages of analysis were performed on the data sets. In stage I, Shapiro-Wilk's test is used to test the normality of the data set. If the data set follows a normal distribution, then a t-test



Last position before clicked:
Grip: 0
Roll/Pitch, axis 1: 0
Roll/Pitch, axis 2: 0
Arm: 0
Shoulder: -567
Base: 413
Set desired speed here: e.g. 1
Enter a number between 1 to 5.

Fig. 5. Overall web page layout of the LabVolt 5150 Robot Teach Pendant.

The robot Home position is described as ______________________?

a. perch position c. pick position
b. starting position d. place position

The robot Perch position ______________.

a. allows product to enter a point to be picked without colliding with the robot shoulder
b. allows product to enter a point to be picked without colliding with the EOAT
c. allows product to enter a point to be picked without colliding with the robot base
d. allows the robot to return to the Home position after each product pick

Fig. 6. Sample pre- and post-test questions for two-year college evaluation.

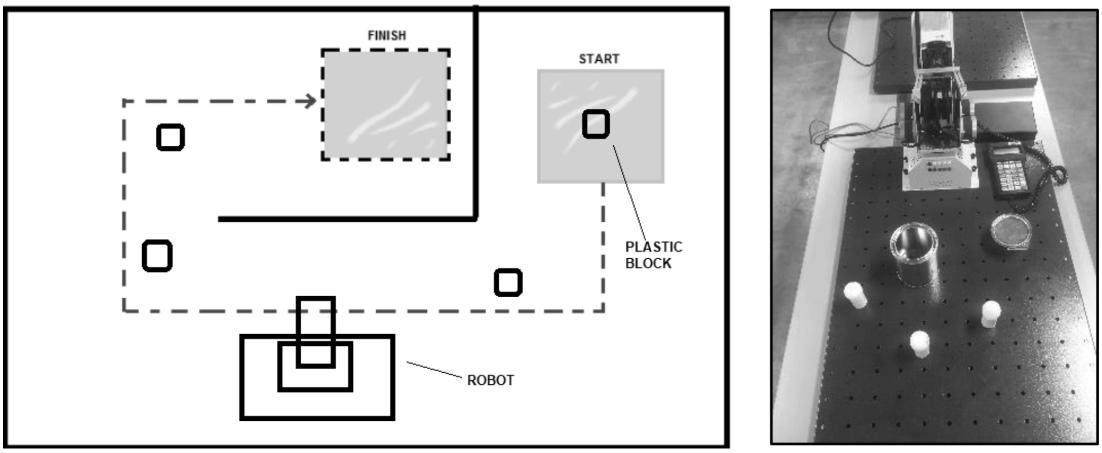


Fig. 7. Layout of lab exercises #1 and 2

can be used to do a paired data comparison. However, if the data set fails the normality test, a Wilcoxon Ranks test should be used to perform paired data comparison. The null hypothesis H_o for stage I is that there is no difference between the distribution of the data set and a normal distribution. The null hypothesis H_o for stage II is that there is no difference between the two sample sets. Two different tests were conducted; ***Test 1*** (before using VTP), and ***Test 2*** (after using VTP).

The analysis results revealed that the null hypothesis was rejected for average test score and standard deviation of test score. This suggests that using the VTP causes significant improvement in learning. Table 1 summarizes the test statistics, critical value and conclusions for each test, where the null hypothesis is $\mu_d = 0$, sample size for VTP is 19, and the α value is 0.05. The average score before and after VTP was 65.00 and 80.50.

6.2 Evaluation by four-year college students (Spring 2019, Fall 2018, and Spring 2018)

Participants. Participants in the pre- and post-testing were four-year college students enrolled in a Manufacturing Automation and Robotics course. All students provided ratings and comments using an opinion survey, and completed a pre- and post-test.

Materials. Students' knowledge of articulated robot anatomy, motion planning and programming a robot using a virtual teaching pendant (VTP) was assessed. Figs. 8 and 9 show sample test questions:

Table 1. Results from t test of means and f test of variance for Virtual Teach Pendant (two-year college students).

	Test statistic	**Critical value**	**Conclusion**
Shapiro-Wilk's Normality Test	0.96	0.01	Do not Reject Null Hypothesis
Before VTP vs. After VTP (t-Test)	4.23	2.11	Reject Null Hypothesis
Before VTP vs. After VTP (F-Test)	2.33	2.27	Reject Null Hypothesis

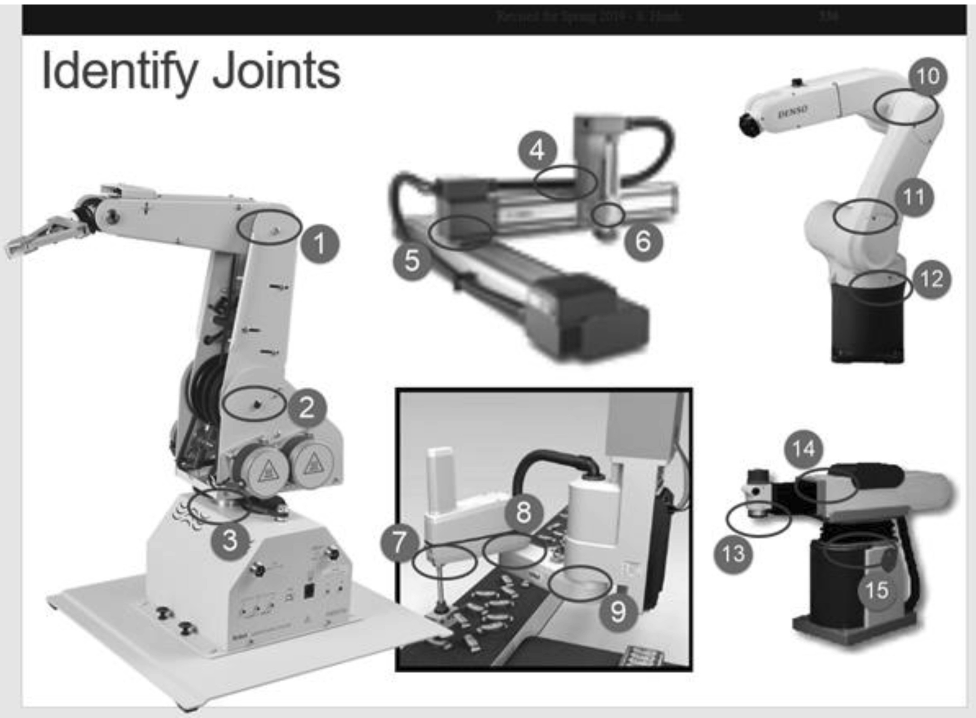
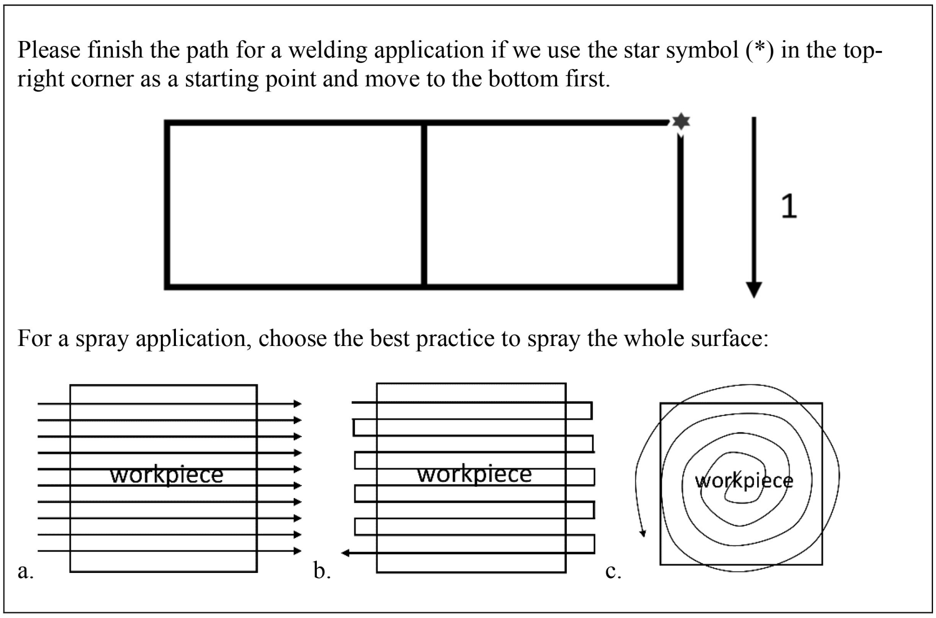


Fig. 8. Sample pre- and post-test question.



Please finish the path for a welding application if we use the star symbol (*) in the top-right corner as a starting point and move to the bottom first.

For a spray application, choose the best practice to spray the whole surface:

Fig. 9. Sample pre- and post-test questions.

Pre and post-test data analysis and results. The pre and post test data were analyzed to see if there was statistically significant score improvement between tests. Two stages of analysis were performed on the data sets. In stage I, Shapiro-Wilk's test is used to test the normality of the data set. If the data set follows a normal distribution, then a t-test can be used to do the paired data comparison. However, if the data set fails the normality test, a Wilcoxon Ranks test should be used to perform paired data comparison. The null hypothesis H_o for stage I is that there is no difference between the distribution of the data set and a normal distribution. The null hypothesis H_o for stage II is that there is no difference between the two sample sets. Two different tests were conducted; ***Test 1*** (before using

Table 2. Results from t test of means and f test of variance for Virtual Teach Pendant (four-year college students, spring 2019)

	Test statistic	Critical value	Conclusion
Shapiro-Wilk Normality Test	0.88	0.01	Do not Reject null hypothesis
Before VTP vs. After VTP (t-Test)	14.18	2.02	Reject Null Hypothesis
Before VTP vs. After VTP (F-Test)	3.30	1.65	Reject Null Hypothesis

Table 3. Results from t test of means and f test of variance for Virtual Teach Pendant (four-year college students, fall 2018)

	Test statistic	Critical value	Conclusion
Shapiro-Wilk Normality Test	0.87	0.01	Do not Reject Null Hypothesis
Before VTP vs. After VTP (t-Test)	14.01	2.00	Reject Null Hypothesis
Before VTP vs. After VTP (F-Test)	4.00	1.56	Reject Null Hypothesis

Table 4. Results from t test of means and f test of variance for Virtual Teach Pendant (four-year college students, spring 2018)

	Test statistic	Critical value	Conclusion
Shapiro-Wilk Normality Test	0.90	0.01	Do not Reject Null Hypothesis
Before VTP vs. After VTP (t-Test)	14.52	2.00	Reject Null Hypothesis
Before VTP vs. After VTP (F-Test)	4.27	1.55	Reject Null Hypothesis

VTP), and ***Test 2*** (after using VTP) for motion planning.

The evaluations took place over three semesters: Spring 2019 (45 participants); Fall 2018 (56 participants); and Spring 2018 (59 participants).

Spring 2019. The analysis results revealed that the null hypothesis was rejected for average test score and standard deviation of test score. This suggests that using the VTP causes significant improvement in learning. Table 2 summarizes the test statistics, critical value and conclusions for each test for Spring 2019 students, where the null hypothesis is $\mu_d = 0$, sample size for VTP is 45, and the α value is 0.05. The average score before and after VTP was 52.67 and 93.33.

Fall 2018. Table 3 summarizes the test statistics, critical value and conclusions for each test for Fall 2018 students, where the null hypothesis is $\mu_d = 0$, sample size for VTP is 56, and the α value is 0.05. The average score before and after VTP was 59.10 and 94.11. Results suggest there is significant learning improvements after VTP exercise.

Spring 2018. Table 4 summarizes the test statistics, critical value and conclusions for each test for Spring 2018 students, where the null hypothesis is $\mu_d = 0$, sample size for VTP is 59, and the α value is 0.05. The average score before and after VTP was 48.10 and 90.20. Results suggest there is significant learning improvements after VTP exercise.

6.3 Opinion survey

High school students. The Virtual Teach Pendant was presented in science, technology and engineering classrooms at six high schools in Texas with a total audience of 150 students. Concepts such as different types of robot configurations, robot applications, robot anatomy, and work envelope were presented. The remote Virtual Tech Pendant was used to illustrate the work envelope of the LabVolt 5050 robot. Volunteers moved the robot to find out the answers.

Due to time constraints, only the opinion survey was administered at the high schools. The mean responses to the survey questions are shown in Fig. 10. Student ratings were positive for all items (n = 150, min 5.43, max 6.08), especially on the question of "more tools like this to help them to learn"—perhaps because only a few were able to use the Virtual Teach Pendant.

Two-year students. Fig. 11 shows opinion survey results for the two-year college students. Their responses were also positive (n = 19, mix. 5.74, max 6.31). Again, the item of "would like more tools like this" ranks highest.

Undergraduate students. The VTP was also used in an upper-level undergraduate class on Manufacturing Automation and Robotics course at a university in Texas as part of a lab exercise. Survey participants (n = 159) had positive responses to VTP (Fig. 12). Again, the item of "would like more tools like this to help me to learn" rated highest.

6.4 Student comments

The opinion survey included two open-ended questions: (1) "The most helpful thing about using Virtual Teaching Pendant was:" and (2) "This experience could be improved if".

In students' responses to the question "The most helpful thing about this project has been:" a common theme was that the hands-on, visual experience was helpful to learning. Below are some sample responses:

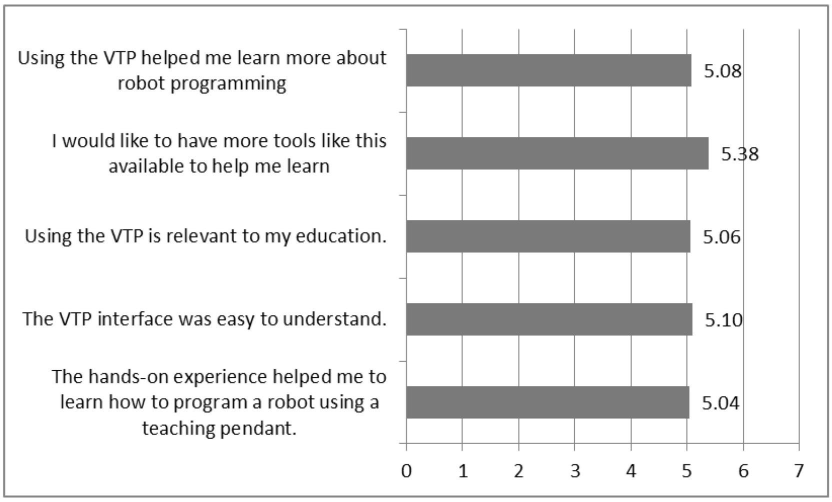


Fig. 10. Virtual Teach Pendant opinion survey results (high school students).

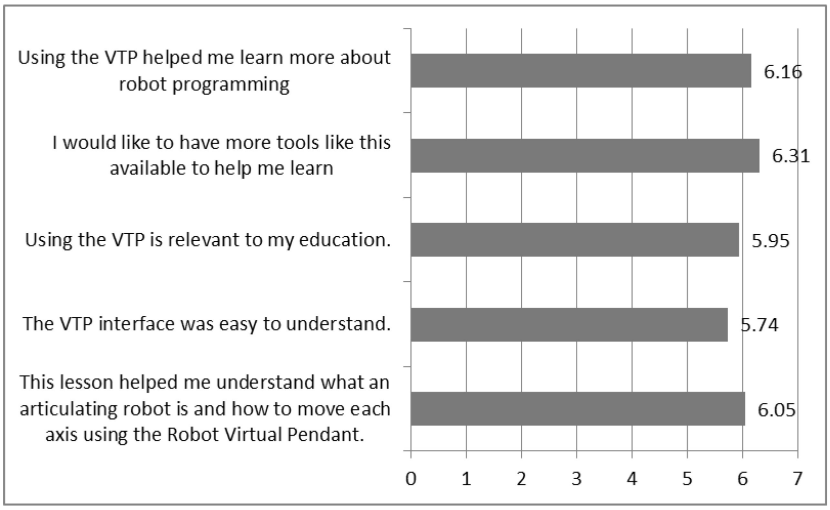


Fig. 11. Virtual Teach Pendant opinion survey results (two-year college students).

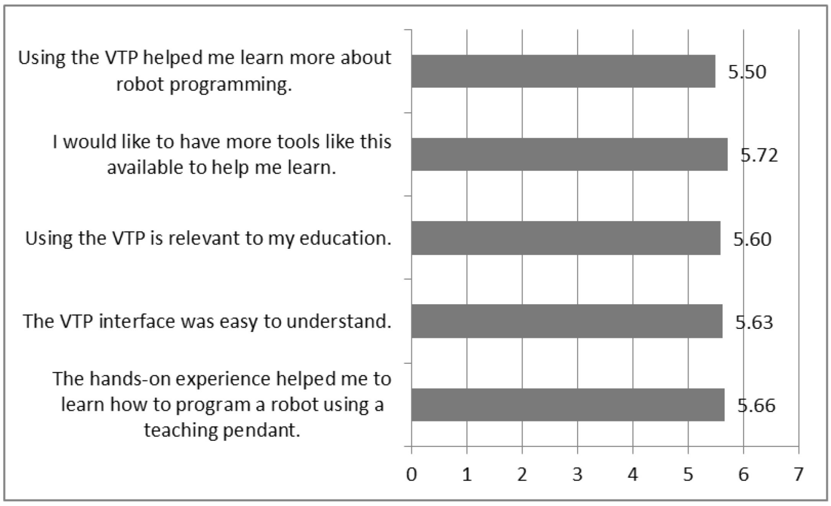


Fig. 12. Virtual Teach Pendant opinion survey results (four-year college students).

- It helped me experience controlling a robot from a remote location.
- It had an easy user interface.
- It allowed us to understand the different movements that a robot can make.
- Remotely viewing the robot that was being controlled made for a better challenge and forced the user to think about the task in order to accomplish it.
- That we were actually using the robot without having to hook it up or physically have it.
- Seeing the robot joints that we covered in class in action.
- Watching the degrees of freedom live
- I was able to utilize the web development program to control the robot in the Texas A&M Lab. This showed me how the IP Address was used to connect over servers to control the robot on another server.
- That it had a live feed on how the robot was moving.
- The easy interface was very helpful in learning how to use the VTP.

In students' responses to the question "This project could be improved by:" common themes were (1) the camera feed needed to be faster; (2) the camera needed to be positioned better relative to the object to be picked up; and (3) it would be helpful to be able to refer to a diagram or labels to be able to remember angles and positions. Sample comments are below:

- A diagram of the robot with rotation angles on it would have eliminated some of the experimentation.
- The camera could be positioned better to see the position of the robot in reference to the cube.
- If it was labeled a little better. As in Grip: open and Grip: closed. I got a little confused every now and then.
- N/A! I think it was great. Maybe more on programming!
- The camera showing the robot had better real time feedback.
- More complex task.
- The lag on the video made the robot more difficult to control.
- The cube was colored and there were multiple camera angles.
- If there was no delay between the controls and the video.
- More programming was involved.

7. Conclusion and future directions

This paper describes the development and evaluation of a remote teach pendant and web server that enables students to do lab exercises remotely. The VTP has been used to help students to become familiar with robot anatomy (joints and links), practice robot motion planning and program a robot remotely to complete simple pick-and-place assembly tasks. The system has been evaluated by high school and undergraduate students at two- and four-year institutions. Pre and post-test and survey results suggest that the system is useful for learning robot anatomy, motion planning, and robot programming; students would like to have more tools like this to help them learn; and the interface is user-friendly and easy to manipulate. The system is currently available to users within our institutional network, and will be made available externally after security arrangements are worked out with our information technology office. The remote access technology has been transferred to two other institutions that use the same robot and the developed materials and lab exercises have been shared with ~120 educators via ten workshops over the past two years.

Future directions may include adding advanced programming functions (such as conditional and loop structures) and a real-time 3D model to show the robot position within the work envelope, and providing haptic feedback. The system may be further enhanced by adding a camera on the gripper to capture a front view of the object of interest; and by adding a voice recognition component to allow users to communicate with the robot via voice. Therefore we can develop an intelligent robot that can pick up a designated object on a table based on user suggestions.

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