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# Remote Laboratories for Automated System Education: Design, Evaluation, and Outreach*

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Studies have shown that authentic learning experiences enhance student interest in a subject and facilitate learning transfer to real-life situations. Because industrial-scale automated systems are expensive, their availability at educational institutions is often very limited. Remote labs can potentially provide more opportunities for hands-on, authentic, and self-paced learning experiences and are especially valuable during a pandemic. This paper describes four remotely accessible automated systems. Instructors from two-year and four-year institutions were invited to participate in a one-day workshop. The workshop included demos of the remote systems and presentations about how these systems were built and being used in the classroom. Eight workshops were held and were attended by a total of 58 instructors. Evaluation results suggest that the workshops were helpful and relevant. Future directions include establishing a network of remotely accessible resources, including lesson plans and links to automated systems.

**Keywords:** remote laboratories; automated systems; faculty professional development; industrial automation education

## 1. Introduction

Laboratory experiences play a critical role in science education [1]. Hands-on experimentation with physical systems is essential to helping students learn; especially, it is an essential part of the manufacturing education program or degree. However, the cost of industrial scale equipment, limited lab time, and large class sizes can limit the availability of this desired experience. The remote lab concept was first proposed in 1991 by a researcher at Purdue University who sought to create a remotely shared control systems lab [2]. Concepts such as simulated physical systems (virtual labs) and remote experimentation using real systems (remote labs) have become more popular with the rise of the Internet [3]. Heradio et al. [4] and Grodotzki et al. [5] conducted a comprehensive literature of virtual and remote laboratory development work up to 2018. 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. 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 [6]. Hsieh has expanded the application of remote labs to industrial automation education by developing several remote labs for automated systems [7–11]. The ability to offer labs remotely has assumed heightened importance in a pandemic environment.

### *1.1 Objectives*

This paper provides an overview of four developed remotely accessible automated systems and a description of the content, evaluation results, and lessons learned from a workshop for two-year and four-year college instructors. The workshop disseminated research findings and learning materials to enable broader adoption of remote lab technology and lay the groundwork for future formation of a remote lab network hosted by a consortium of institutions who can share resources and common practices. We will conclude by describing plans for future endeavors.

## 2. Remotely Accessible Automated Systems

Five automated systems have been developed and made available remotely since 2017, including a Festo automated system [7], LabVolt robot teach pendant [8], MTW 3D Printer for CNC education [9], Ultimaker 3D Printer [10], and a Mack injection molding machine [11]. All five systems share a similar generic remote control system architecture (RCSA), but customized code was written to control each specific machine.

The RCSA includes the following components: (1) web server, (2) user interface, (3) equipment-to-web-server interface, and (4) web-browser-to-web-server interface. For example, in Fig. 1, a robot is the system to be controlled; Apache is the web server; a Logitech joystick is the remote control unit and a JavaScript communication application serves as the interface between client and web pages; Visual Basic and MySQL applications are used to interface the web server with the robot controller;

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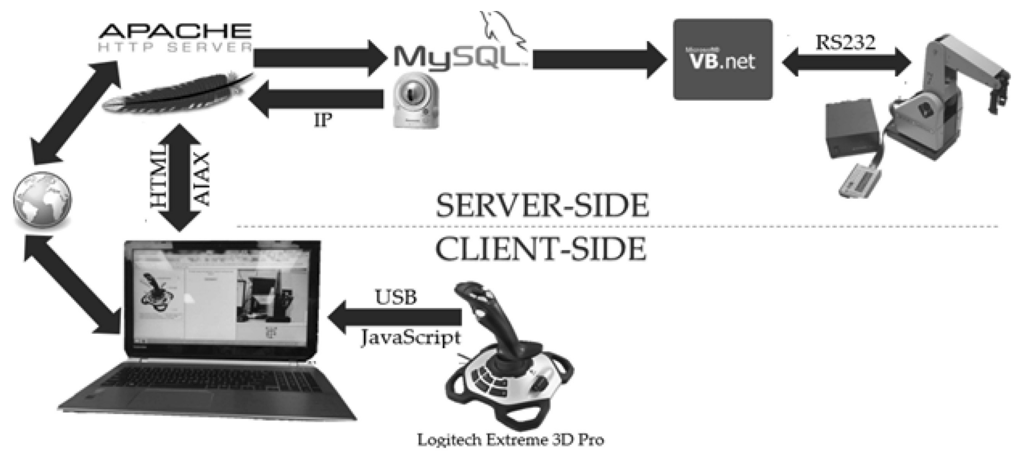


**Fig. 1.** Generic Remote Control System Architecture (RCSA).

and the interface between the web browser and web server are web pages developed using PHP script language (HTML and AJAX).

While it might seem more straightforward to use newer development boards (such as ESP32) that can host their own website, often existing systems that need to be made remotely accessible have proprietary control boards and control languages (instead of a more generic board such as Arduino). The architecture described above provides a solution in these instances.

Following are brief descriptions of the physical setup and functions of four remotely controlled systems. The descriptions also include links to lab exercises and technical details for three of the systems. The developed software can be shared upon request.

Development of these systems began before the COVID-19 pandemic. The initial goal was to alleviate issues with equipment availability due to large class sizes and limited lab time within undergraduate-level courses such as Manufacturing Automation & Robotics and Introduction to CAD/CAM. Teaching conditions during the height of the pandemic accelerated their deployment; students used them to complete lab assignments from their homes. With the resumption of in-person instruction, the systems are currently being used to supplement in-person labs.

### *2.1 Ultimaker 3D Printer*

The Ultimaker 3D printer comes with a built in camera with an isometric view of the work space with the 3D printer. Custom code was written to link a web page with a controller. The printer comes with its own specific API language. The remote system was designed not only to allow access to 3D printing but also to help users learn how a CNC machine works, since 3D printers and CNC machines both use G-Code. In theory, a 3D printer is a type of CNC machine, in that G-code is used to position its tool (extruder).

For learning G-Code, a marker is attached to the printer head. Remote users send basic CNC G-Code to the printer, which causes the printer head to draw with the marker. The user can view the marking process through the webcams. The setup allow users to run CNC code line by line as well as process an entire CNC G-code job. Fig. 2 shows the remote 3D system components and physical setup.

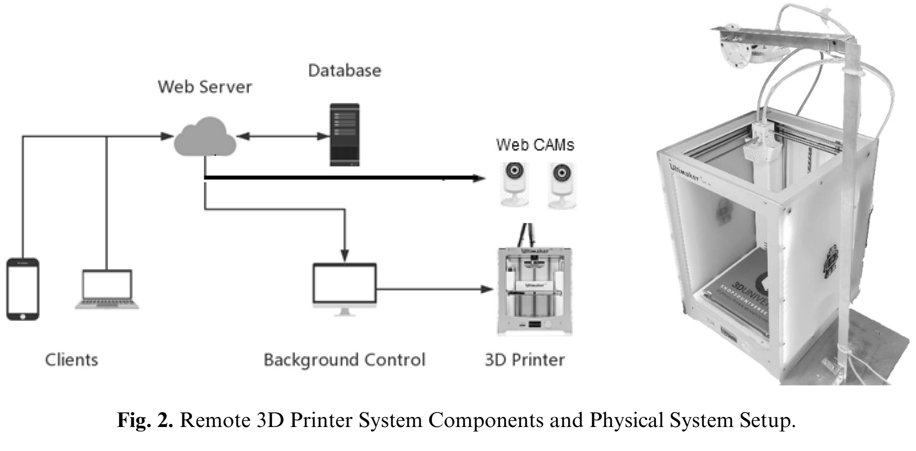
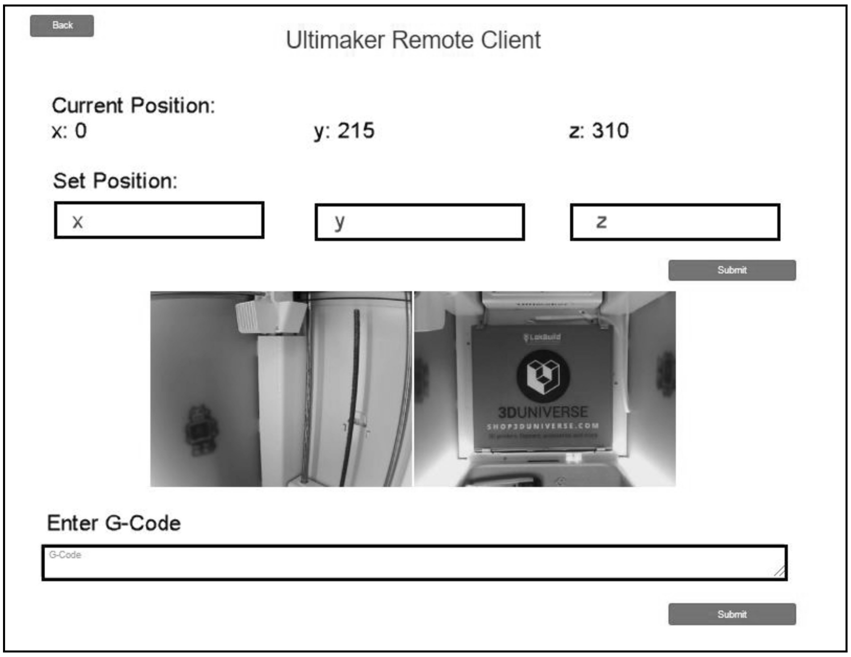


**Fig. 2.** Remote 3D Printer System Components and Physical System Setup.



Ultimaker Remote Client

Current Position:
x: 0 y: 215 z: 310

Set Position:

**Fig. 3.** Web Interface for Remote Control of Ultimaker 3D Printer.

Users can register to obtain a user name and password to login to the system. On the Printer main page, users have four options: (1) View Temperature, (2) Print, (3) Camera Feed, or (4) Manual Movement. There are additional options within each sub-menu. For example, the View Temperature web page allow the user to view the bed temperature as well as extruder temperature. Fig. 3 shows the web interface for remote control of the printer.

As a lab exercise, remote students used G-code to move the extruder in a linear motion (G1) and a counterclockwise arch motion (G3). Instructions were as follows:

1. Go to the "Enter G-Code" section at the bottom.
2. Type "G28" and click "Submit" at first.
3. Type "G0 X130 Y50" and click "Submit".
4. Type "G3 X50 Y130 I-80 J0" and click "Submit".
5. Take a screenshot.
6. Type "G28" and click "Submit" to move the extruder back to the home position.

Fig. 4 shows a screen capture of the 3D printer executing sample G-Code.

Lab exercises created for this system include 1) 3D Printing and Remote Control; 2) Design and Create 3D Model for 3D Printer; and 3) Print 3D Model on 3D Printer remotely. These exercises cover basic operations of the remote system and are available on the author's Remote Control of Ultimaker 3D printer web page [12]. The web page also includes detailed information about how the system was built.

**Fig. 4.** Remote Views of Printer Head and Completed Drawing After CNC Coding Exercise.

### 2.2 Mack Injection Molding Machine

Many household products are produced using injection molding machines. In educational settings, injection molding machines are used to teach mold design, properties of materials, manufacturing processes. Injection molding provides a good case study for courses related to automated system design, such as CAD/CAM Production Systems. The machine used for the remote system was designed to be manually operated. To allow the machine to be accessed remotely, an automated mode was added.

The architecture of the physical system is shown in Fig.5. The air supply is connected to the pressure control valve, which sends pressure readings to, and accepts settings from, an Arduino controller. The regulated compressed air is then sent to a directional valve's inlet, which is controlled by the Arduino again to either extend or retract the piston. The heater is controlled in the same fashion as the pressure regulator, except it is temperature that is being regulated. The motorized clamp is driven by a stepper through a motor drive. The Arduino itself has two-way communication with the web server.

The remote user interface is shown in Fig. 6. The interface allows users to (1) turn the system on and off; (2) control the solenoid to move the position forward and backwards; (3) set the temperature of the furnace and air pressure for the piston; and (4) monitor system operation via webcam images. The following controls are available:

- Power button.
- Piston control buttons, extend and retract.
- Mold clamp motor buttons, up and down.
- Heater temperature gauge and air pressure gauge
- Heater temperature control slider and pressure setting slider.

The layout was designed to be as similar to the actual equipment as possible. The heater temperature and air pressure gauges use an analog dial-like display that resembles the gauges on the injection molding machine. Sliders are used to control the temperature and pressure of the equipment remotely. The right side includes two camera views that provide top and side views of the remote equipment.

The application is a single-page app built using Jinja template engine and rendered by Flask. The event handling on the front-end is handled by a Socket IO JavaScript module. A Cascading Style Sheet (CSS) was used for the grid design to provide flexible layouts. Using CSS makes arranging and aligning elements relatively easy and allows the interface to adjust to fit various screen sizes.

Lab exercises created for this system include (1) Injection Molding Machine and Remote Control; and (2) Remote Operation of Injection Molding Machine. These exercises cover basic operations of the remote system and are available on the author's Remote Control of Injection Molding Machine web page [13]. The web page also includes information about how the system was built.

### 2.3 LabVolt Teach Pendant

A teach pendant is a commonly used and inexpensive method of programming industrial robots. A remote virtual teach pendant was developed to

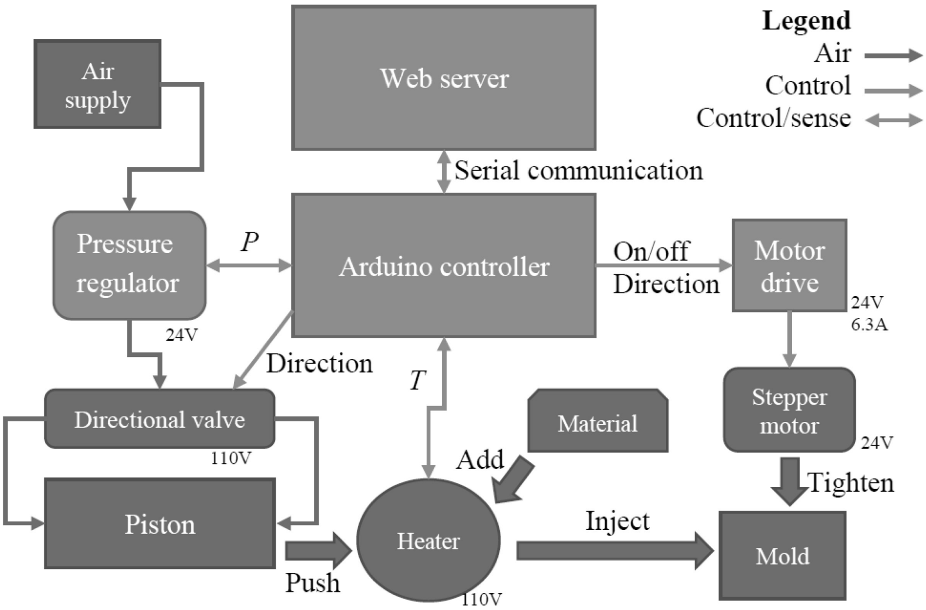


**Fig. 5.** System Architecture for Remotely Accessible Injection Molding Machine.

**Fig. 6.** Graphical User Interface for Remotely Controlled Injection Molding System

allow students to define a path by specifying coordinates of points, then save the program and play it back at different speeds from a remote location. The pendant helps students to learn robot anatomy concepts such as joints, limits, control resolution and work envelope; to practice robot motion planning; and to program a robot to complete simple pick-and-place assembly tasks [3]. Fig. 7 provides an overview of the system. After logging in, the user can press symbols representing each joint of the robot (Fig. 8). Based on these 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.

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 [6].

Lab exercises created for this system include (1) Multi-Camera Monitoring and Remote Control Web Page Design; and (2) Remote Control of LabVolt Robot. These exercises cover basic opera-

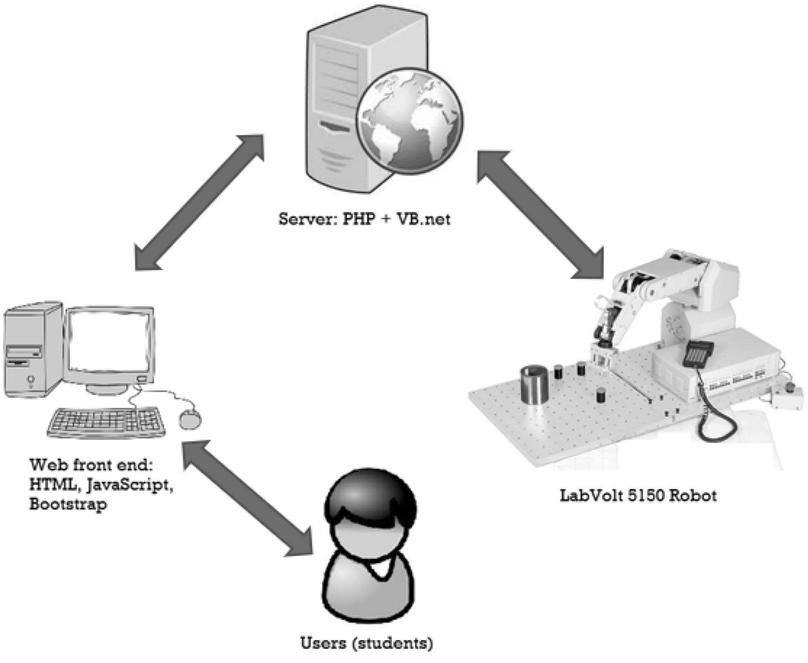
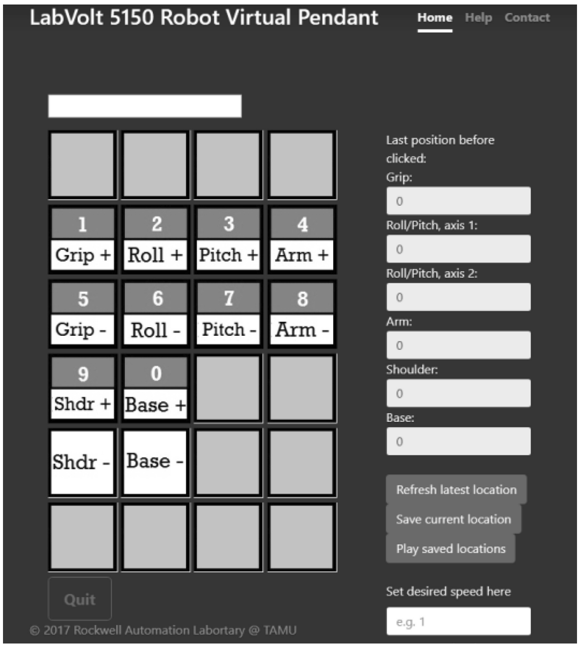


**Fig. 7.** Overview of Virtual Teach Pendant system.



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. 8.** Remote User Interface for Virtual Teach Pendant.

tions of the remote system and are available on the author's Remote Control of LabVolt Articulated Robot web page [14]. The web page also includes information about how the system was built.

### *2.4 Festo Pick-and-Place Automated Color Sorting System*

Pick-and-place operations are commonly used in manufacturing processes. This system was developed to demonstrate a scaled-up automated assembly system controlled by a programmable logic controller that can do color sorting and pick-and-place by color. Remote students can control the system and observe the entire sorting and assembly process.

The automated sorting and assembly system consists of two conveyors, two feeders and one pick-and-place pneumatic robot station. All components are controlled and synchronized by three Allen Bradley MicroLogix 1000 programmable logic controllers, as shown in Fig. 9. The PLCs are connected to the stations through ribbon cables via Festo Easy Ports and then to field devices as shown in Fig. 10.

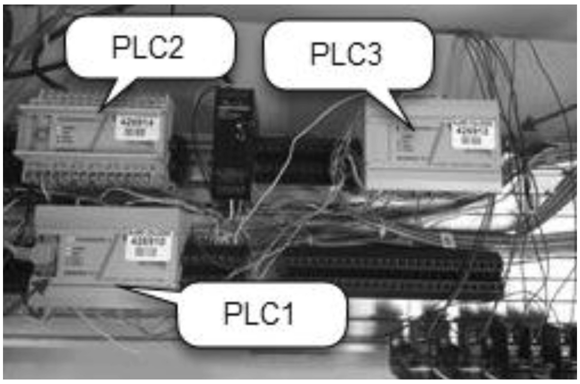


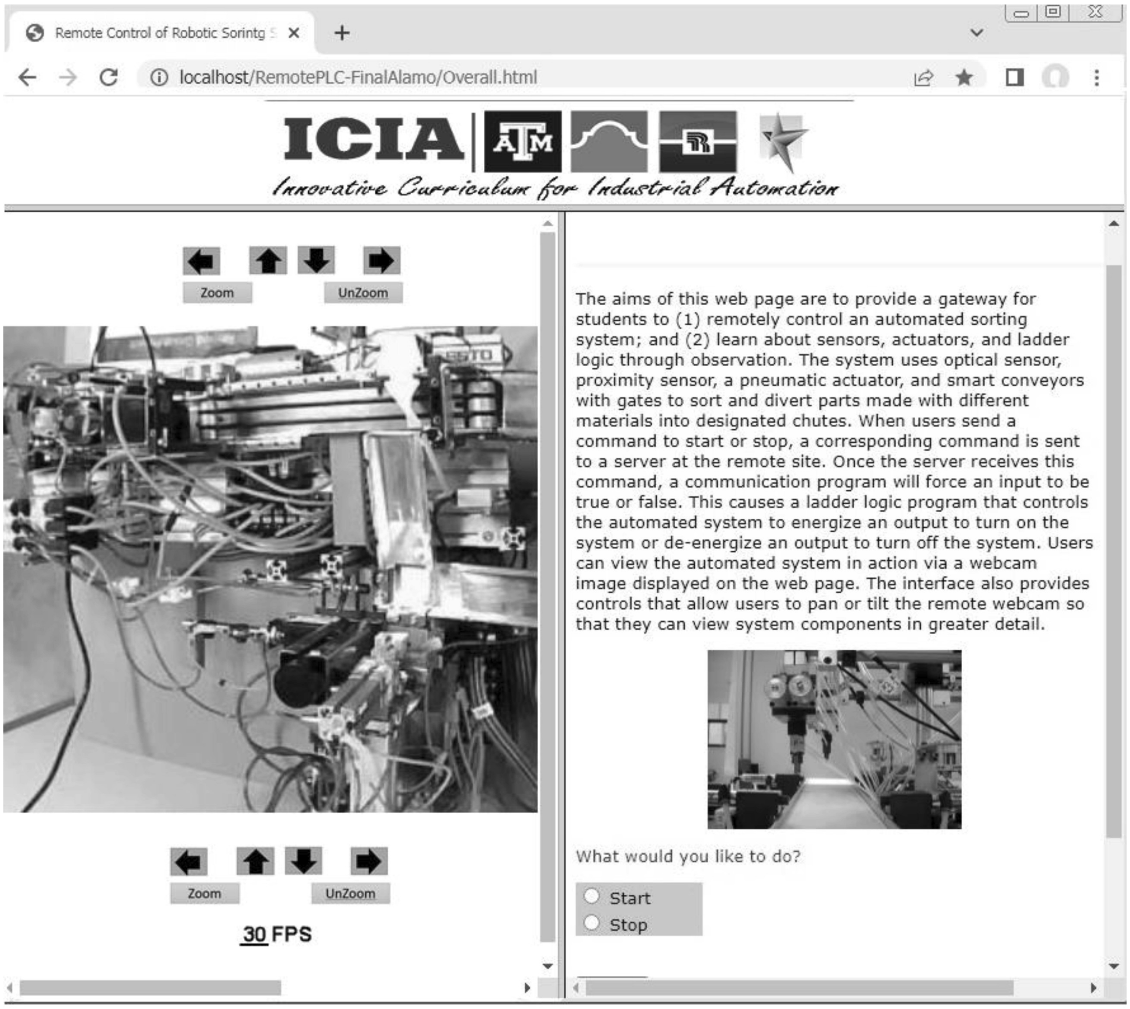
**Fig. 9.** Allen-Bradley PLCs Used for Remote Control of Festo System.

**Fig. 10.** Ribbon Cable Connections Between Festo Easy Port and Field Devices.

PLC1 controls the base feeder, sorting conveyor and the diverter gate solenoid for the feeder/sorting station. When the PLC receives a "Start" signal from a remote user, the feeder fiber optic sensor detects the presence of parts in the feeder, the feeder cylinder extends and pushes a part into the path of the in-feed Optic Photo Eye (OPE). When the OPE detects the part, it energizes the sorting station conveyor motor. The sorting conveyor moves the part and passes it in front of an Inductive Proximity Switch (IND). If the part is plastic, it is passed on through to the plastic base assembly station; however, if it is metal, the IND detects this and causes the diverter gate solenoid to energize and diverts the metal base to the metal base assembly station. The PLC then retracts the base feeder cylinder, which completes the cycle of this station.

PLC2 is used for sensor inputs, to control the cap feeder, and to control the transfer cylinder for the metal assembly station. When a metal base enters the assembly station, another Optic Photo Eye detects that it is present and PLC2 extends the cap feeder and provides a cap to the robot of the metal assembly station. At the end of the robot arm cycle, PLC2 retracts the cap feeder cylinder and the PLC causes the metal part transfer cylinder to extend, which transfers the part across a chute and onto the outfeed conveyor. This is the end of the metal assembly station cycle.

PLC3 controls the pick-and-place robot assembly process in the metal assembly station. When a metal base is present and a cap has been fed from the cap feeder, the pick-and-place robot arm moves down to pick up the cap, closes the jaws to grasp the



The aims of this web page are to provide a gateway for students to (1) remotely control an automated sorting system; and (2) learn about sensors, actuators, and ladder logic through observation. The system uses optical sensor, proximity sensor, a pneumatic actuator, and smart conveyors with gates to sort and divert parts made with different materials into designated chutes. When users send a command to start or stop, a corresponding command is sent to a server at the remote site. Once the server receives this command, a communication program will force an input to be true or false. This causes a ladder logic program that controls the automated system to energize an output to turn on the system or de-energize an output to turn off the system. Users can view the automated system in action via a webcam image displayed on the web page. The interface also provides controls that allow users to pan or tilt the remote webcam so that they can view system components in greater detail.

What would you like to do?

○ Start
○ Stop

**Fig. 11.** Remote User Interface for Festo Pick-and-Place Automated Sorting System.

cap, moves to the top/home position, moves to the extended/top position, moves to the extended/down position to place the cap on the base, opens the jaws to release the cap, moves to the extended/top position, and returns to top/home position. To provide control for the operation, the PLC utilizes inputs from various sensors to monitor the operation while sending outputs to various devices to control the operation.

Remote control of the automated system is accomplished through a dedicated web server that hosts the web pages and allows guests to log into a web page to "Start" and "Stop" the system while viewing the operations in real time through a camera that is mounted above the system, as shown in Fig. 11.

The system framework was built and tested by students at The Alamo Colleges in San Antonio. There were 38 students in the course. The majority of the students participating in the course were dual-credit high school students. A survey was conducted to gauge student response to the teaching methods used. The survey indicated that the hands-on portion of the training greatly helped them understand and visualize programming using the robot teach pendant. In addition, (1) students seemed interested and intrigued by the set up; (2) there is a time-delay between the control action and the image being presented over the webcam; and (3) students wanted more time to use the system.

## 3. Instructor Workshop on Remotely Accessible Automated Systems

A workshop was offered to showcase the remotely accessible automated systems to two-year college instructors and show them how to make an automated system remotely accessible.

### *3.1 Participants*

To recruit interested participants from relevant areas for the workshop, a flyer was distributed to engineering and engineering technology commu-

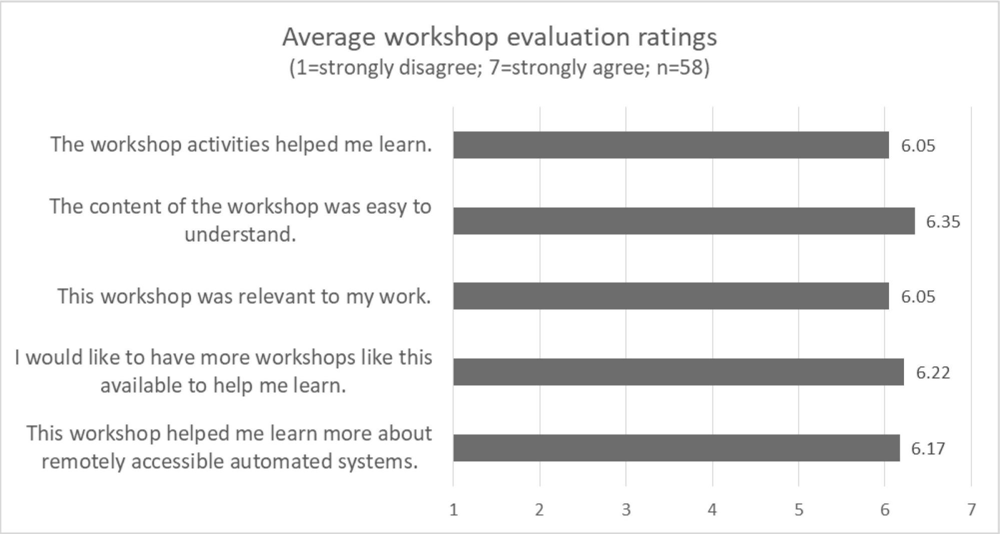


**Fig. 12.** Average Ratings for Instructor Workshop (7-Point Scale).

nities such as the American Society for Engineering Education (ASEE) Engineering Technology listserv (ETD-L) and national Advanced Technological Education (ATE) centers such as the Florida ATE Center (FLATE). The flyer described the content of the workshop, date/time, location, and included a link to an application form. The application form collected the applicant's contact information, educational background, current teaching focus, and plans for using the workshop content. This information was used to select instructors with relevant backgrounds, teaching focus, and plans to use the workshop content. Selected instructors were sent an invitation to attend the workshop and received a small stipend to help cover their travel expenses.

### *3.2 Agenda*

The one-day long workshop ran from 8:45AM to 4:30PM with a one hour lunch break, and was hosted by one of the project's two-year college collaborators. Eight workshops were offered. Typical events included (1) pre-workshop networking; (2) greeting from a dean of the hosting college; (3) self-introductions; (4) presentations about how remote systems are built, (5) demonstrations of remote systems, (6) a group project that allowed participants to practice using a remote system; (7) tour of the hosting college facilities, (8) lunch break and networking, and (9) post workshop survey. The PI and instructors from the collaborating two-year institutions took turns showcasing remote systems that they had built. In addition, a related online lab or group project was assigned after each presentation. So for each system presented, there was a lab activity immediately afterwards to enhance the learning experience.

### *3.3 Workshop Evaluation*

The workshops were evaluated by 58 college instructors who completed an opinion survey at the end of the day. The survey asked attendees to rate various aspects of the workshop on a Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree).

- This workshop helped me learn more about remotely accessible automated systems.
- I would like to have more workshops like this available to help me learn.
- This workshop was relevant to my work.
- The content of the workshop was easy to understand.
- The workshop activities helped me learn.

The survey also included two open-ended response questions:

- The most helpful thing about this workshop was _________ .
- This workshop could be improved by _________ .

Average workshop ratings are shown in Fig. 12. Results suggests that participants liked all aspects of the workshop. Notably, the item "Content of the workshop was easy to understand" had an average rating of 6.35 out of 7.

Themes in participants' comments regarding "the most helpful thing about this workshop" included: (1) the opportunity for hands-on interaction with the remote systems; (2) being able to see multiple examples of remote systems in action; (3) the technical and instructional materials included in the hand-outs and USB drive; (4) learning real-world details about the successes and failures when using remote labs in the classroom; (5) the opportunity for Q&A with instructors on the panel; and (6) the lab tours.

In participants' comments about areas for improvement, several indicated a desire for a longer workshop so that they could see more examples, have more hands-on activities, and learn more details about how the remote systems were built and work. Other suggestions included (1) add more cameras to the remote system so they could get other views of the system; (2) add a factory tour; and (3) add a discussion of security issues.

## 4. Conclusion and Future Directions

Remote labs, virtual labs, and in-person labs all have benefits and can be used to teach different aspects of automated systems. Specifically, remotely accessible automated systems are a useful educational tool when an authentic experience with equipment is needed, but equipment availability is limited due to resource or travel limitations. In addition, with the rise of the Internet and Industry 4.0, remote control, diagnosis, and troubleshooting of automated systems are increasingly common in industry. Using remote systems to learn exposes students to real-life limitations such as time lags, and therefore helps prepare them for future work.

This paper described four remotely accessible automated systems that have been developed and are being used by undergraduate students enrolled in Manufacturing Automation & Robotics and Introduction to CAD/CAM courses. A one-day workshop for two-year and four-year college instructors was offered to demonstrate these systems and disseminate knowledge about how to build them. The workshop was well-received.

Future directions include finding ways to continue to provide technical support to the participating institutions so that the adopted materials can have a long-term impact on students' learning experience. We will also look into simplifying the remote control system architecture for the injection molding system by using a web-aware development board with the Arduino controller. Finally, we plan to work toward forming a national network of remote labs. Institutions within the network can share their remote labs/systems and learning materials. This effort would potentially increase collaboration efforts and reduce the need for individual institutions to buy and maintain equipment.

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