2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #38816

Design and Evaluation of Modules to Teach PLC Interfacing Concepts

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Design and Evaluation of Modules to Teach PLC Interfacing Concepts

Integrating the components of an automated system is a complex and multi-faceted cognitive skill. Instructional technologies are being used successfully to teach some aspects of system integration, such as PLC programming and system design. However, there has been relatively little emphasis on developing technologies to help students learn about the devices and machines that make up systems, interfacing, and system troubleshooting. Students typically get their first exposure to PLC interfacing during labs. Making the correct connections between a PLC and the various types of input/output devices, bridging devices, machine controllers, machine vision systems, human machine interface (HMI) panels, and power supplies can be confusing and intimidating. Students often spend precious lab time waiting for an instructor to check a circuit or answer a question. An integrated problem-solving environment (I-PSE) is being developed to address this gap.

This paper presents the design, development, and evaluation of several interactive web-based instructional modules to help students learn PLC interfacing concepts such as ladder logic and I/O devices, basic wiring, and interfacing with bridge devices. Groups of learners ranging from 34 to 65 individuals reviewed the modules. They completed pre- and post-tests to assess instructional effectiveness, a survey to provide feedback about the design and usefulness of the modules, and a self-assessment of their knowledge of I/O interfacing concepts. Results suggest that the modules have a positive impact on student learning. In addition, the self-efficacy survey results suggest that the experience of using the modules—together with lectures and labs—has a strong positive impact on learners' self-efficacy related to writing ladder logic and interfacing I/O devices.

Motivation

Automated system integration involves the design, interface, and troubleshooting of an automated system—such as a robotic welding system, which integrates a robot, conveyor, fixture, sensors, and actuators for loading and unloading parts. The ability to integrate components and devices to form an automated system is a complex and multi-faceted cognitive skill. New automation and control engineers are often not fully prepared to perform system integration tasks. For example, recent studies by Deloitte and The Manufacturing Institute note that the U.S. faces a need for nearly 2.4 million manufacturing positions to be filled by 2028 [1]. In addition, in May 2019, Deloitte surveyed 523 executives in a range of industries in 26 countries across the globe on their intelligent automation strategies and the impact on their workforces. Results suggest that over the next three years, executives expect automation to increase their workforce capacity by 27%, which is equivalent to 2.4 million additional full-time employees [2]. Needed are methods for helping students to develop system integration skills reliably and efficiently.

What is system integration?

System integration refers to all the tasks related to designing, interface, and troubleshooting an automated manufacturing system. An automated manufacturing system generally consists of processing equipment, material handling devices, and material transfer equipment [3]. The processing equipment can be a computer numerical control (CNC) milling, lathe, turning machine or any other type of equipment that changes or alters the property of the work piece. Material handling devices include industrial robots, actuators, and others devices that handle the work-in-process work-piece at the workstations. Material transfer equipment, such as conveyors, is often used to move raw materials from bins to a destination where they can be picked up by material handling devices. A system controller works behind the scenes to orchestrate and synchronize equipment operations.

Control engineers must possess several layers of knowledge. First, they must know about hardware devices (e.g., sensors and motors) and equipment input/output (I/O) ports that can serve as input or output (I/O) devices to a programmable logic controller (PLC). They do not necessarily need to know about specific brands or models, but they do need to know functions and general characteristics.

Second**,** control engineers need to understand how to interface external devices and equipment to the controller. I/O devices and equipment I/O ports are connected to a PLC via I/O modules. A PLC may have several I/O modules. Engineers need to understand the circuitry involved and whether or not bridging devices—such as relays, optical isolators, or solid-state relays—will be needed. For example, if an external device is AC driven and its input module is DC powered, then a bridging device—such as a solid-state relay—is needed. Also, they need to know about the I/O ports of the equipment to be interfaced, normal states of their electrical contacts (normally open or closed), voltage/current specifications, and sinking or sourcing type of connections.

Third, control engineers need to understand how PLC programming works. Unlike processors in office computers, PLC processors constantly monitor the status of their I/O devices and process all lines of PLC programs—for all practical purposes—simultaneously. Programming PLCs requires knowledge of ladder logic, a specialized language for industry automation and control. Ladder logic provides a straightforward way for people who already understand how to wire devices to program complex control system applications, but can be challenging for those who are unfamiliar with wiring. Control engineers need to be able to translate problem requirements into ladder logic to orchestrate and synchronize the process being automated.

Fourth, control engineers need to be able to troubleshoot system problems due to interface and/or programming issues. This requires understanding how the system is supposed to work, what things can go wrong, and how to test for certain types for problems, as well as general troubleshooting skills. Expert engineers use this knowledge to build systems to automate a process within specified operational parameters and resources. Results from a previous investigation of how expert and novice engineers approach conceptual design of an automated system suggest that to develop expertise, novices need: 1) support to help them remember steps to be automated; 2) exposure to a wide range of automation case studies to help them understand what is typically involved in automating various types of processes and why; 3) opportunities for practice so that knowing what factors to consider in coming up with a design solution is automatic [4].

Instructional technologies for Automated System Integration education

Instructional technologies that teach control of automated systems using programmable logic controller (PLC) programming are available. For example, an educational software product called LogixPro 500 sold by TheLearningPit, employs animations of processes, such as traffic control and batch mixing, to illustrate how ladder logic relates to an automated process [5]. Students can start and stop the animations and study the corresponding ladder logic for certain conditions or cases.

Integrated Virtual Learning System for Programmable Logic Controller (Virtual PLC)—developed by the PI for a previous NSF award—uses a variety of instructional approaches, including animations, simulations, intelligent tutors, and games to teach about PLC concepts and programming [6]. As with LogixPro 500, students can view animations of processes and study the corresponding control programs. In addition, they can use a ladder logic toolkit to write and test their own control programs. In every evaluation so far, students have made statistically significant learning gains as a result of using the system, and rated the modules positively in terms of ease of use and understanding, clear objectives, amount of interaction, ability to motivate, relevance, and pace [7-9]. In addition, VirtualPLC is widely used in academia and industry; as of early 2016, there were 3119 registered users from 97 two-year colleges, 170 four-year colleges and universities, 8 educational centers, and 118 companies—including several international institutions and companies (registration is no longer required to use Virtual PLC).

Hsieh and Deotale [10] designed a problem-solving environment (PSE) for students to learn about automated system design. This environment allows students to design systems to automate continuous, discrete, and batch manufacturing processes, and combinations thereof (hybrid processes). The focus is on allocating work content and selecting equipment for each station, designing the layout of the stations to form an assembly line, and line balancing—given a desired production rate and minimizing investment cost and line imbalance. The results suggest that PSE virtual environments that allow students to visualize processes and participate in realistic problem-solving are engaging and beneficial to learning.

The learning technologies above focus on control programming and conceptual design. There has been little emphasis on development of technologies to help students learn about automated system integration (i.e. device and machine characteristics, how to interface PLCs with devices and machines, and troubleshooting). Students typically get their first exposure to PLC interfacing during labs. Making the correct connections between a PLC and the various types of input/output devices, bridging devices, machine controllers, machine vision systems, human machine interface (HMI) panels, and power supplies can be confusing and intimidating.

To address this gap, the author's team is building an integrated, adaptive, and web-based problem-solving environment (I-PSE) known as Automated System Integration Tutor (ASI Tutor). ASI Tutor will include 1) interactive web-based instructional modules to help students learn PLC interfacing concepts such as ladder logic and I/O devices, basic wiring, and interfacing with bridge devices; 2) an intelligent tutoring system; and 3) virtual/remote labs. These modules will be inter-connected and designed to support one another with a goal of increasing user interaction and engagement. The focus of this paper is on the design, development, and evaluation of interactive web-based instructional modules on interfacing concepts and a case study.

The 13 modules below were designed and developed in 2021-22:

- Interfacing Concepts
- PLC Introduction
- PLC Image Table
- Timer Instructions: TON
- Timer Instructions: TOF
- Timer Instructions: RTO
- Basic Wiring: Input Module
- Basic Wiring: Output Module
- Basic Wiring: Interface Game v1
- Basic Wiring: Interface Game v2
- Interface with Bridge Device: Relay with PNP Sensor
- Interface with Bridge Device: Relay with Optical Sensor
- Case Study: Widget Assembly

The modules are available at https://people.tamu.edu/~hsieh/ASI-Tutor/. This paper briefly describes the user interface (UI) prototyping, the design of the interfacing exercises, and the evaluation process for these modules.

UI Prototyping

During this phase, we asked students to help evaluate prototype UI designs for teaching PLC interfacing concepts. Students were asked to review three alternative UI designs, choose the one they thought was best, explain why, and provide additional comments if desired. The designs varied in the way help is made available and are shown in Figures 1-3.

- In UI Design #1, when users need help, they click a Help button (a circle with a letter I). A new page then opens to display instructions. To return to the original page, users click the browser Back button.
- In UI Design #2, when users need help, they click a Help button. Instructions appear in a pop-up window. To return to the original page, users close the pop-up window.
- In UI Design #3, when users need help, they hover the mouse pointer over a Help button. Instructions appear in a pop-up window. To return to the original page, users close the pop-up window.

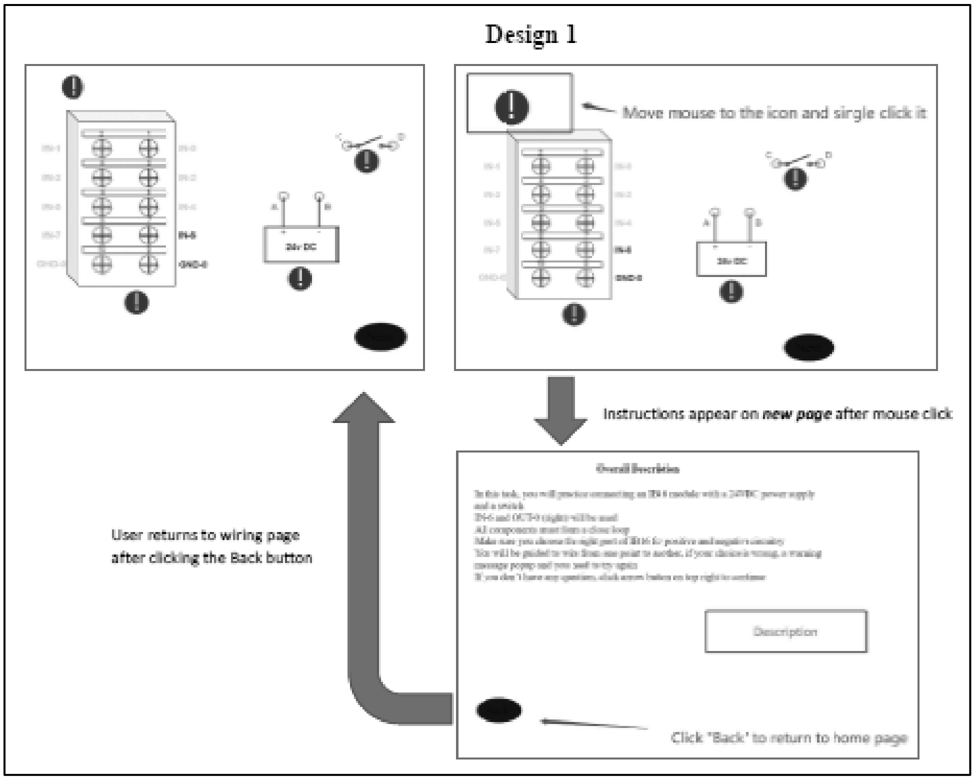


Figure 1. UI design #1.

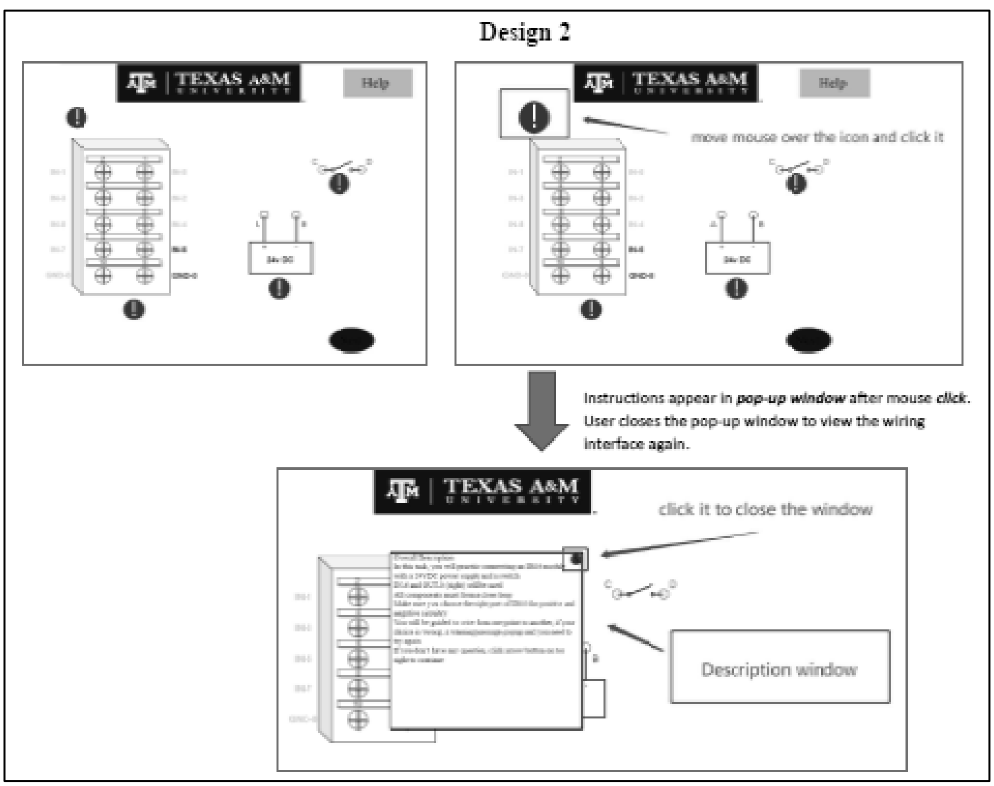


Figure 2. UI design #2.

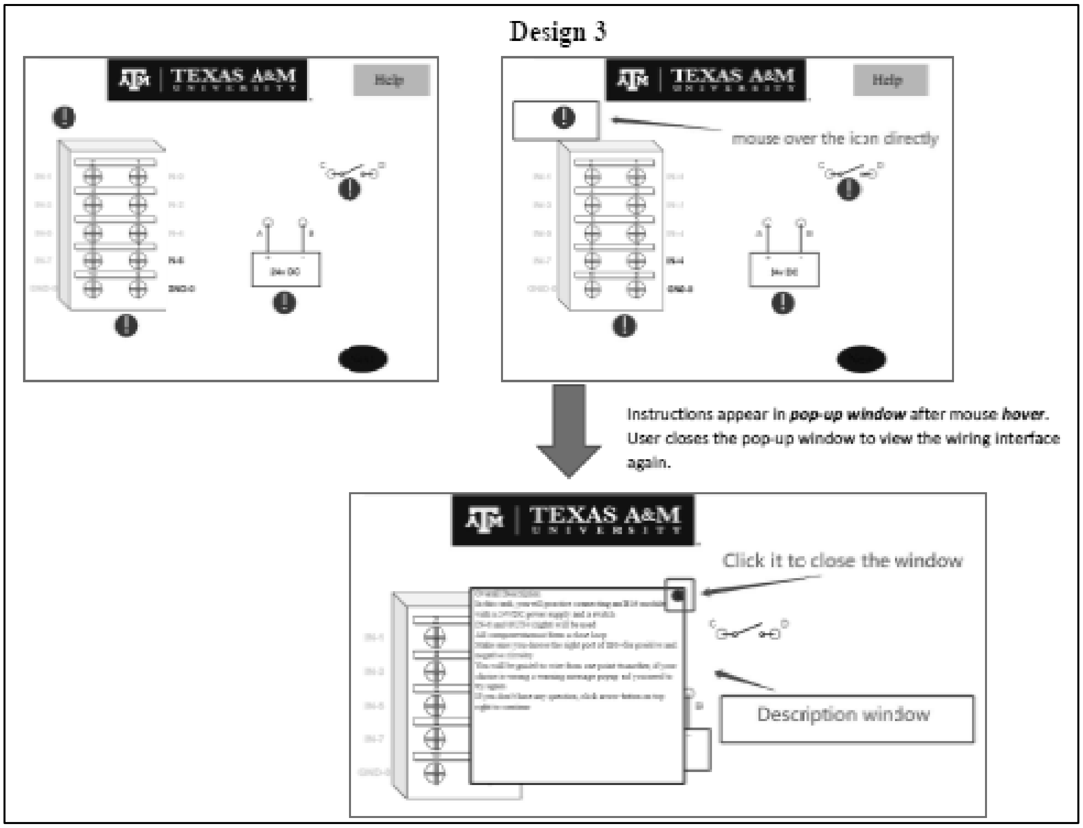


Figure 3. UI design #3.

Results

Of the 48 students who participated in the UI design prototyping activity, none chose Design #1, 13 chose Design #3, and 35 chose Design #2.

The most common reason given for not choosing Design #1 was that it creates a new page. Students used words like “inconvenient,” “jarring,” “annoying,” and “cumbersome” to describe their impressions of this design. Some added that the new page would cover/obscure the wiring diagram.

Of the participants who chose Design #3, the most common reason given was that they preferred the convenience of hovering rather than clicking.

The most common reason given for choosing Design #2 instead of Design #3 was concern about opening a pop-up window unintentionally while hovering and then having click to close it. A few commented that if the pop-up window would automatically close when the mouse pointer hovers away the pop-up, they would like Design #3 most.

Some students who chose Designs #2 or #3 added that they liked seeing the instructions alongside the image of the wiring (instead of covering it as in Design #1).

Summary

Based on results from interface prototyping, Design #2 was used in developing the UI for the interfacing exercises.

Design and Evaluation of Modules on PLC interfacing

This section describes the design of the modules for teaching 1) basic wiring, including practice on interfacing PLC input and output modules with switches and motors; and 2) interfacing bridge devices such as PNP and optical sensors with a PLC.

<u>Modules on Basic Wiring</u>

Design and development. The basic wiring modules are intended to teach how to interface input and output devices such as switches and motors with a PLC. Interfacing a PLC with I/O devices is an essential skill for building and integrating automated systems. The module design includes three frames representing three steps. Step 1 describes the principles of interfacing a particular type of device. Step 2 shows learners how to interface devices correctly. Step 3 allows user to practice interfacing devices with a PLC. Learners can hover over components to learn about them and click on the Help icon to familiarize themselves with the steps to making a successful interface attempt. The interfacing task is foolproof in that the wires will not stick to a terminal unless the correct terminal is selected. Figure 4 shows screenshots of the modules.

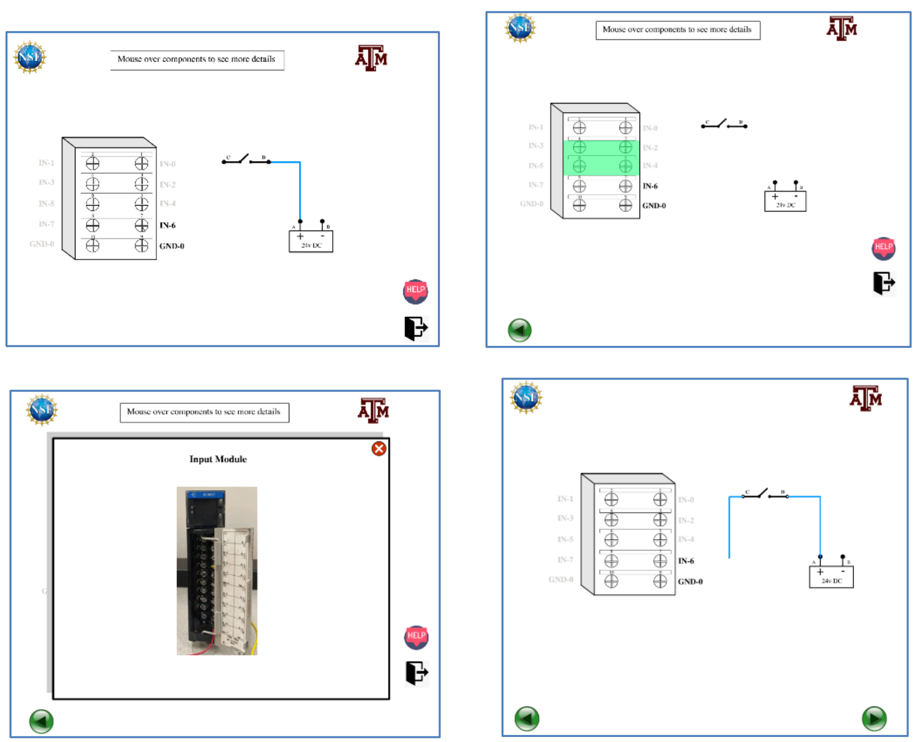


Figure 4. Screenshots illustrating animation, hovering, physical device, and foolproof interface concept.

The developed modules are available at the links below:

- Input module: http://people.tamu.edu/~hsieh/ASI-Tutor/asit-Wiring/IOInterface/IB16-N-OB8-V2/ib16/ib16.html
- Output module: http://people.tamu.edu/~hsieh/ASI-Tutor/asit-Wiring/IOInterface/IB16-N-OB8-V2/ob8/ob8.html

Evaluation. Students completed a pre-test before using the input and output modules and a post-test afterwards (n=65). The mean scores for the pre- and post-tests, respectively, were 50.77% and 99.16%. The result of a 1-tailed paired t-test was 1.2E-12, indicating a significant difference in means ($p < 0.001$). The result of an f-test was 2.7E-62, indicating a significant difference in variance ($p<0.001$).

Mean	50.76923077	99.15384615
SD	35.35533906	0
f-test		2.71092E-62
1-tailed paired t-test		1.19738E-12

Future work. Animations will be used to show the correct way of interfacing I/O modules to the PLC. In addition, learners will be able to click on a "Show Me the Work" icon to view a video of the instructor performing the interfacing on physical equipment and/or a video showing the devices and modules being used in an industrial setting.

Modules on Interfacing with Bridge Devices

Design and development. Often I/O devices have a different power rating than the I/O modules provided by industrial controllers such as PLCs. When this happens, a bridge device, such as a relay, is needed to enable the I/O devices to be integrated with the industrial controller. However, this increases the complexity of the interfacing task. The design of the bridge device modules uses the three-step approach used in the Input/Output Interface Modules (described above). Because the interfacing task is more complicated, the wires are color coded to make the correct terminals more obvious (Figure 5).

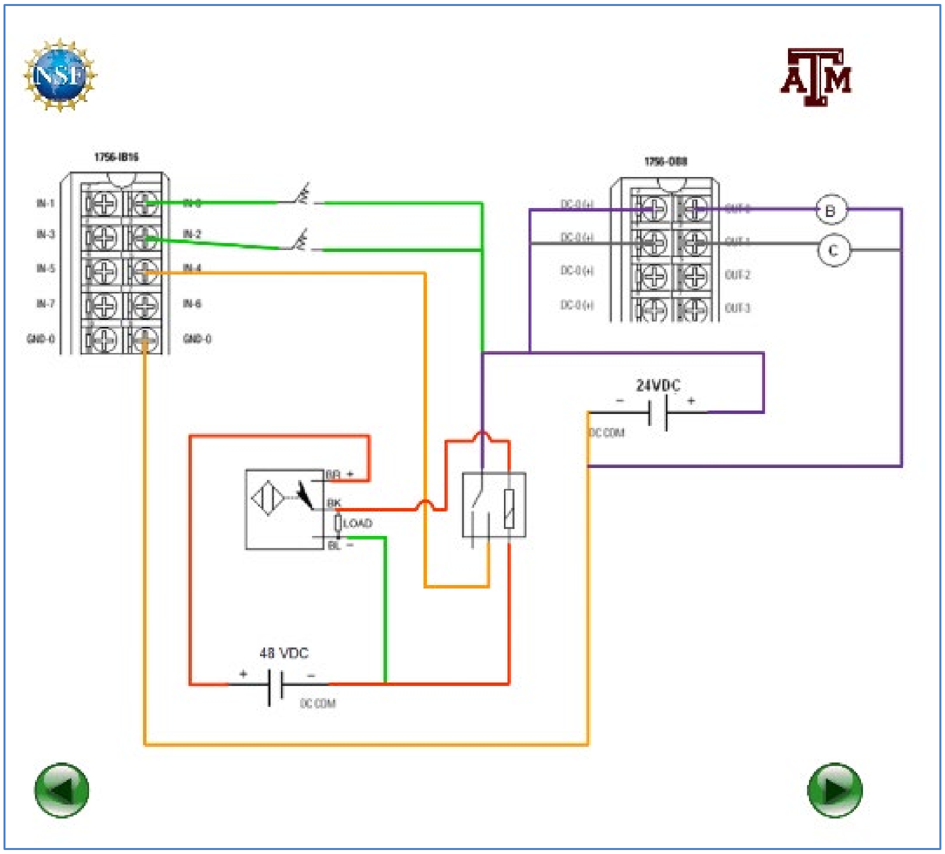


Figure 5. Color Coded Wiring to Enhance Visualization of Interfacing Task

The developed modules are available at the links below:

- Relay with PNP Sensor: http://people.tamu.edu/~hsieh/ASI-Tutor/asit-Wiring/PNPRelayInputModule/io_relay_sensor.html
- Relay with Optical Sensor: https://people.tamu.edu/~hsieh/ASI-Tutor/asit-Wiring/IOInterface/Interruptor-N-Reflector-w-IB16/Practice_Connection_Extra.html

Evaluation. The Relay with PNP Sensor module was evaluated. The evaluation included pre- and post-tests to assess learning outcomes and a survey.

Pre- and post-tests.. Students completed a pre-test before using the module and a post-test afterwards (n=50). The mean scores for the pre- and post-tests, respectively, were 54.90% and 96.06%. The result of a 1-tailed paired t-test was 4.2E-10, indicating a significant difference in means (p < 0.001). The result of an f-test was 1.4E-29, indicating a significant difference in variance (p<0.001).

Mean	54.9	96.06
SD	31.81980515	3.5355339
f-test		1.368E-29
1-tailed paired t-test		4.179E-10

Survey. The survey asked students to rate aspects of the module and to respond to open-ended questions about desired features and suggestions for improvement.

Ratings. Although 50 students completed the pre- and post-tests, because of time constraints, only 5 completed the survey. Figure 6 provides the mean ratings for the Likert-scale questions (1= strongly disagree; 7 = strongly agree) on the survey.

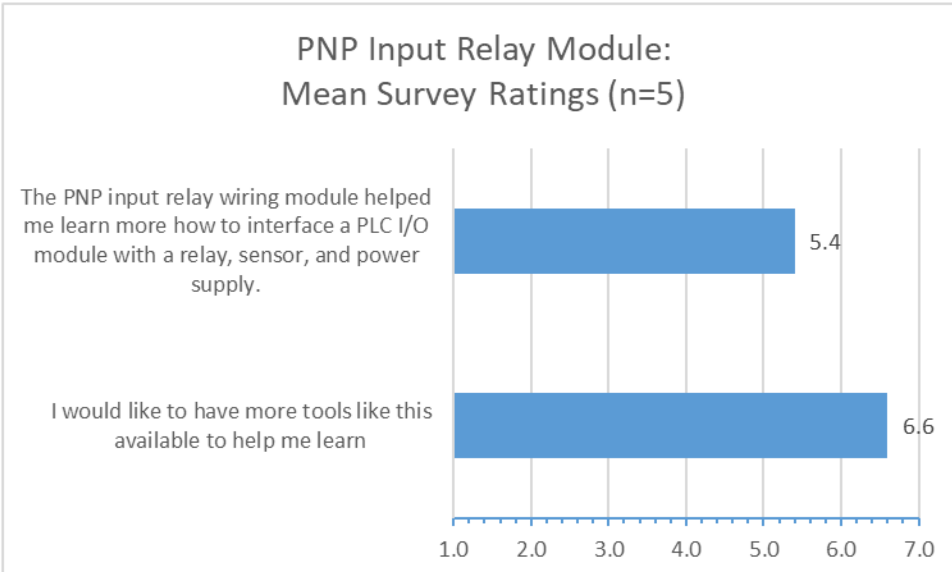


Figure 6. Mean survey ratings for PNP Input Relay module

Survey question responses. The survey included four open-response questions.

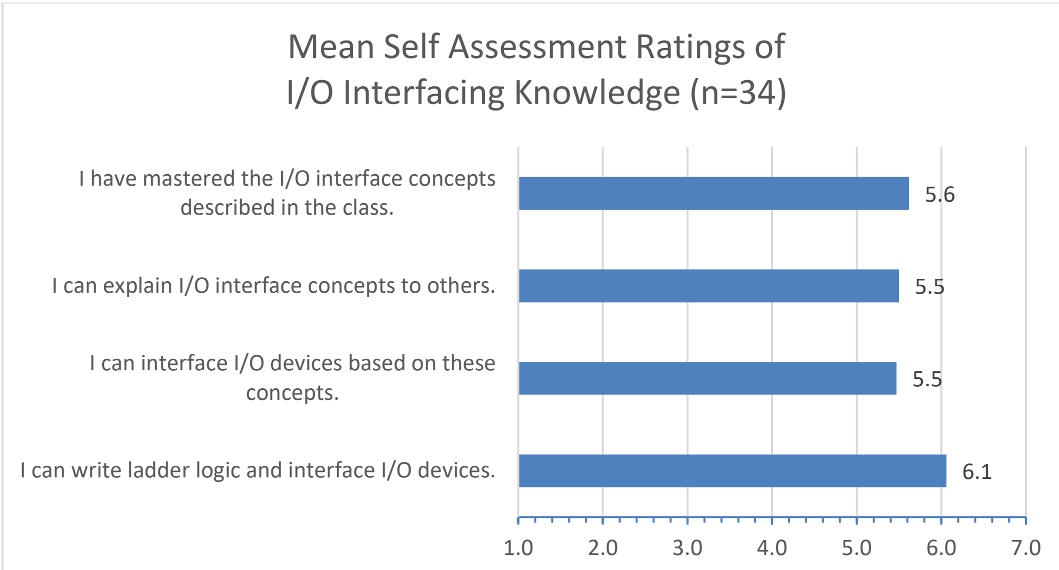
1. *Were there any additional buttons or controls that you wish you had? If so, please describe*. The most common response was to include buttons to access hints or explanations for why something needs to be connected a certain way.
2. *Was there anything about the module that was difficult to understand? If so, please describe*. The most common response was No. One student noted that the connection between the power supply and other components was difficult to understand.
3. *What was the most helpful thing about the wiring module?* The most common responses were the opportunity to practice and the ability to visualize the wiring.
4. *How could the wiring module be improved?* One student said it would be helpful to see the wiring colors separately.

Future work. Planned improvements include (1) provide explanatory information about why the wiring needs to be a certain way; (2) adding a sequence number to each wire; (3) showing the interface steps in a to do list; (4) eliminating each step as it is completed, (5) adding a video showing an someone interfacing a physical module, sensors, and relay, and (6) adding real-life video of the circuit being used in an industrial setting.

Evaluation of Overall Learning Experience on Topic of Interfacing Concepts

The ASI Tutor modules on interfacing concepts were used in the context of lectures and labs on interfacing. To assess self-efficacy, at the end of the semester, 34 students completed a self-assessment of their knowledge of I/O interfacing concepts. The assessment consisted of four Likert-scale questions to assess self-efficacy and three open-response questions.

Survey Ratings. Figure 7 provides the mean ratings for the Likert-scale questions (1= strongly disagree; 7 = strongly agree).



The mean ratings suggest that using the ASI Tutor modules in conjunction with the lectures and labs on interfacing components of automated systems has a strong positive effect on learners' self-efficacy related to writing ladder logic and interfacing I/O devices (6.1/7.0), and a moderately strong effect on learners' self-efficacy related to mastering the I/O interface concepts described in class (5.6/7.0), explaining I/O concepts to others (5.5/7.0), and interfacing I/O devices based on these concepts (5.5/7.0).

Survey Question Responses. The survey included three open-response questions.

1. **What was the most helpful thing about the I/O interfacing modules/lectures?**
   Answers to this question fell into the following categories
   - Many opportunities for interactive, hands-on practice
   - Explanations
   - Ability to visualize how ladder logic and interfacing relate to making systems work.
   - Seeing examples of real-world applications
   - Learning about industry jobs related to this area

2. **Was there anything about the modules/lectures that was difficult to understand? If so, please describe.**
   Answers to this question fell into the following categories:
   - Wiring diagrams sometimes difficult to understand. Would like additional explanation about why some wiring connections are wrong.
   - PLC symbols
   - Lectures sometimes presented too much information at once.

- Would like to know more about physical I/O modules (e.g., selection and installation) and relays.

3. **Were there any additional modules/lectures that you wish you had? If so, please describe.**
   Answers to this question fell into the following categories:

   - Would like more content about topics such as human-machine interfacing and sensors; physical connections and integration to machines such as robots; temperature/lighting
   - Additional examples and lab exercises
   - More practice on PLC programming

Summary

The pre-and post-test results suggest that the ASI Tutor modules on interfacing have a positive impact on student learning. In addition, the self-efficacy survey results suggest that the experience of using ASI Tutor—together with lectures and labs—has a strong positive impact on learners' self-efficacy related to writing ladder logic and interfacing I/O devices.

Overall, the response to ASI Tutor has been very positive. Based on student comments, the features of ASI Tutor that contribute most to learning how to interface automated system components include 1) providing a large number and variety of questions for practice; 2) providing detailed explanations about correct answers; 3) providing timely feedback; 4) the ability to visualize how ladder logic and wiring diagrams relate to one another; and 5) ability to view an animation of the wiring process.

The most commonly suggested improvements were: 1) bug fixes; 2) provide more explanation about why incorrect wiring is incorrect; and 3) provide more practice questions. In other words, the gist of the suggested improvements are basically to do more of the things that were positive and do them even better.

Future directions include implementation of the improvements above; development of new modules focusing on interfacing other devices (such as robots); and development of modules focused on industrial applications of automated systems—such as manufacturing systems—to help learners see the big picture of how systems are integrated.

Acknowledgements

This material was supported by the National Science Foundation's Improving Undergraduate STEM Education (IUSE) Program (award no. 2044449). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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