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Design, Construction, and Evaluation of Portable Programmable Logic Controller (PLC) Kit for Industrial Automation and Control Education*

SHENG-JEN ("Tony") HSIEH
3367 TAMU, Texas A&M University, College Station, TX, 77843-3367, USA. E-mail: hsieh@tamu.edu

A low-cost portable programmable logic controller (PLC) kit consisting of a controller module and three swappable special function modules – Basic I/O, Sensor, and Automated System – was designed, built, and evaluated. The special function modules can be quickly connected to or disconnected from the controller module to teach different aspects of automation and control, including PLC programming fundamentals, sensor applications in automation, I/O interfacing, and system integration concepts. The kits were used within an upper-level undergraduate manufacturing automation and robotics course to provide students the opportunity to practice programming fundamentals while still in the classroom and for a system integration project in which students built small-scale working models of automated systems. Kits with Basic I/O and Sensor modules were evaluated by 80 students and kits with the Automated System modules were evaluated by 12 students. Evaluation results suggest that the Portable PLC kit is both usable and useful for helping students to practice PLC programming concepts. Students appreciated the opportunity to immediately practice concepts taught during lecture and to visualize results. In addition, students who used Portable PLC to build an automated system found the experience to be helpful for understanding how to interface devices and for integrating the concepts learned in class.

Keywords: programmable logic controller; automated systems; industrial automation education

1. Introduction

Advanced manufacturing technologies are essential to the U.S. economy [1]. According to U.S. Census Bureau reports, in 2020, the U.S. exported $20.0 billion in advanced technology products in the flexible manufacturing category – up 22% from $16.5 billion in 2016 and $16.1 billion in 2015 [2, 3]. This trend is likely to continue to rise as the manufacturing sector becomes increasingly automated and transitions to Industry 4.0 technologies. However, skilled engineers who can operate, maintain, design and build such systems are increasingly difficult to find, even though industrial automation jobs tend to pay well than other professionals [4–6].

Hsieh [7] surveyed 150 industry partners on skill sets needed for careers in industrial automation. Of these, 78 responded that their companies employ technicians or engineers who maintain automated manufacturing systems as part of their job. Of these 78 participants, the majority (about 88%) indicated that their primary market segment/industry includes one of the following: oil & gas, automotive, semiconductor & electronics, energy storage and distribution, metals, or machine builder. Almost half (47%) indicated that their job level was manager or above; the rest were primarily either engineers or technicians. The most commonly reported challenge by far – noted by over half of the respondents – was recruiting and retaining skilled technicians and engineers. Programmable logic control (PLC) programming and system integration and automation were among the most desired skills. Several respondents commented that new hires need to be able to use PLCs; experience with hobbyist kits such as Arduino is not sufficient. Table 1 compares Arduino with Micrologix 1000, which is a small PLC that can be used for industry applications [8, 9].

A PLC is a solid-state control system with a user-programmable memory, used to read input conditions and set output conditions to control a machine or process [10]. PLCs are at the heart of every automated and semi-automated manufacturing system. They make process automation possible by orchestrating and synchronizing processes to ensure that every activity happens in a controlled and coordinated manner. PLC programming is quite different from programming in languages such as Java or C. To write a PLC program, engineers need to know not only PLC programming syntax, but also the functions and general characteristics of the many hardware devices (such as different types of sensors and motors) that can serve as input or output (I/O) devices.

To become proficient at PLC programming, engineering students need to become familiar with functions and general characteristics of hardware devices, to understand how PLC controllers process programs, to be able to interface I/O devices with a PLC, and to be able to understand the control requirements of an application and write control

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Table 1. Comparison of Arduino with MicroLogix 1000 Series PLC

	Arduino	**MicroLogix 1000**
Cost	Low: around $20–$40	High: around $500–$700
Operating voltage	3.3V, 5V	24V, 110V
Programming language	C / C++	Ladder logic
Application	Amateur. Can be used for hobby or small scientific projects for quick deployment.	Industrial. Focus is on industry-level I/O manipulation.
Flexibility	High	Moderate
Reliability	Moderate	High
Other	Can accomplish complex logic and programs; but can lead to unexpected or unstable results. C language is more versatile.	Relatively simple logic; robust and easy to debug and maintain. Designed for industrial environment conditions. Work with communication protocols.

programs accordingly. Hands-on experience with PLCs and I/O devices is needed to develop these skills. Although programmable logic controllers are not large devices, they need to be interfaced with input/output (I/O) devices – such as motors, conveyers, actuators, and robot arms – to operate. The I/O devices can be bulky and expensive. As a result, student access to hands-on PLC training is heavily dependent on lab and equipment availability.

One approach to alleviating limitations in equipment availability is to make PLC education virtual. For example, LogixPro employs animated educational simulations of processes, such as traffic control and batch mixing, to show how a ladder diagram relates to an automated process [11]. Students can start and stop the animations, and study the corresponding ladder diagram for certain conditions or cases. Hsieh has developed an Integrated Virtual Learning System for Programmable Logic Controller (Virtual PLC). This web-based system uses a combination of animations, simulations, intelligent tutoring system technology, and games to teach about programmable logic controllers [12–14].

Virtual learning environments can be used to help students learn simple PLC programming concepts. However, for learning to write complex programs, there is no good substitute for hands-on experience programming a physical system. Needed are compact configurations of PLC and I/O devices that can be used outside of laboratory environments. This paper describes the design, construction, and evaluation of a low-cost portable PLC kit designed and fabricated by the author's research team. The kit consists of a controller module and three swappable, quick connect/disconnect special function modules for teaching different aspects of automation and control, including PLC programming fundamentals, sensor applications in automation, I/O interfacing, and system integration concepts. The kit can be used in the classroom or for remote learning.

Portable configurations of equipment for hands-on learning have been used to teach engineering-related topics such as electrical circuits [15]; introductory electronics, industrial instrumentation, and automation [161]; guidance and control [17]; and lean manufacturing [18]. However, there has been relatively little published work related to portable PLC kits or other compact PLC configurations. The author initially reported his work in this area in 2015 [19]. Since that time, others have undertaken similar efforts [20–23]. This paper continues and builds upon the author's earlier work and includes evaluation data. In addition, a distinctive element of this work is the idea of swappable special function modules that can be quickly connected or disconnected from the controller module to teach different subject matter. For example, the basic I/O module with push button, switches and lights can be used to teach PLC programming; the sensor module can be used to teach PLC programming with sensor applications in automation; and the automated system module can be used to teach I/O interfacing and system integration concepts.

2. Description of Kit

The kit consists of a controller module and three swappable quick connect/disconnect special function modules. The kit, modules, and associated instructional materials were designed and built by the author and his team as part of a U.S. National Science Foundation award. To build the kit, commercially available items such as a controller, power supply, sensors, switches, lights, and wiring were integrated and packaged into a small case with a handle. When closed, the dimensions of the case are 24 x 35 x 14 cm (9.5 x 13.8 x 5.5 in). The total cost of the components used to build a kit ranges from $300–$700 USD, depending on the type of kit. The kits are not currently commercially available.

Within the case, the controller module is on one side and the special function module is on the other

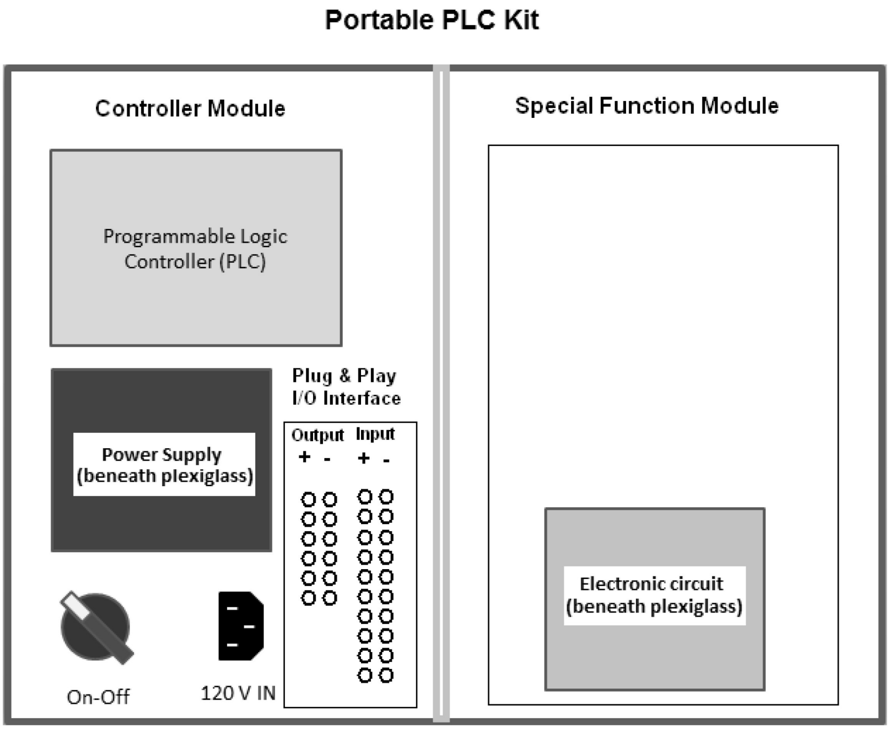


Fig. 1. Diagram of Portable PLC kit layout.

side (Fig. 1). The special function modules include (1) basic I/O module, (2) sensor module, and (3) automated systems module. The automated systems module additionally comes with supplies for building a model, such as a Fischertechnik construction kit.

2.1 Basic Input/output (I/O) Module

The basic I/O module allows students to practice ladder logic programming using basic input and output devices. Input devices include push buttons, switches, limit switches, and thumbwheel switches. The output devices are electric indicator lights. An instructor can use this module to teach PLC programming instructions such as relay instructions, timer and counter instructions, math and compare instructions, and sequential input and output instructions. Fig. 2 is a photo of a PLC kit with a basic I/O module.

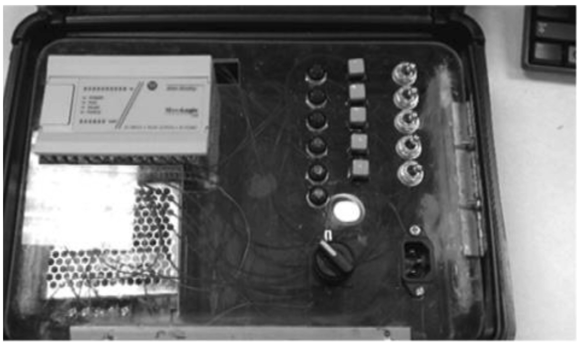


Fig. 2. Portable PLC kit with Basic I/O module on right. The module includes push buttons, switches and lights; a power on/off switch; and a plug outlet. The wiring is housed beneath a Plexiglas cover.

2.2 Sensor Module

The sensor module includes commonly used sensors such as RTDs, thermistors, thermocouples, optical sensors (optical interrupter and reflector), and proximity sensors. Output devices can include lights, small motors, mechanical relays, solid state relays, horns, whistles, and solenoids. Instructors can use this module to teach principles of sensor technology, how to interface sensors to a PLC, and how to program a PLC for real-life applications that utilize sensors, such as motion detection. Fig. 3 shows a portable PLC kit with a sensor module with the following sensors: inductive proximity sensor, resistance temperature detector (RTD), thermistor, thermocouple, optical reflector, optical interrupter, and photocell. Fig. 4 shows a block diagram of the system.

To operate the sensor module, the power cable needs to be plugged in and the switch next to the power plug socket turned on. The "power" LED on the PLC and the two LED displays to the right of the panel will come on.

Thermal sensors. To use the thermal sensors, users touch the model with their hands or other dry object with a temperature that is higher or lower than room temperature. The sensor module also

Fig. 3. Portable PLC Kit with Sensor module on the right. The module includes an inductive proximity sensor, resistance temperature detector (RTD), thermistor, thermocouple, optical reflector, optical interrupter, and photocell.

includes a small light bulb that can be pulled out and used as a heat source.

The thermistor is the upper left resistor-like sensor in the middle of the panel. It is connected to the ohmmeter via a two-position switch. Its resistance changes according to temperature. Users access it by (a) changing the two-position switch to the top position, (b) touching the sensor with an object (such as a finger), (c) reading the resistance from the ohmmeter, and (d) converting it to a temperature based on the sensor's datasheet.

The RTD is the middle (smallest) of the three sensors in the middle of the panel. It is connected to the ohmmeter via a two-position switch. Its resistance changes according to temperature. Users access it by (a) changing the two-position switch to the button position, (b) touching the sensor with an object (such as a finger), (c) reading the resistance from the ohmmeter, and (d) converting it to a temperature based on the sensor's datasheet.

The thermocouple is the lower probe-like sensor of the three sensors in the middle of the panel. It's connected to the voltmeter via an amplifier IC. It generates mV level electric potential difference according to temperature. This voltage is captured and amplified by the IC and then measured by the voltmeter. Users access it by (a) touching the thermocouple with a cold or warm object, (b) reading the voltage (in volts) from the voltmeter, and (c) converting the voltage to temperature according to the IC's specification.

Proximity sensors. To use the proximity sensors,

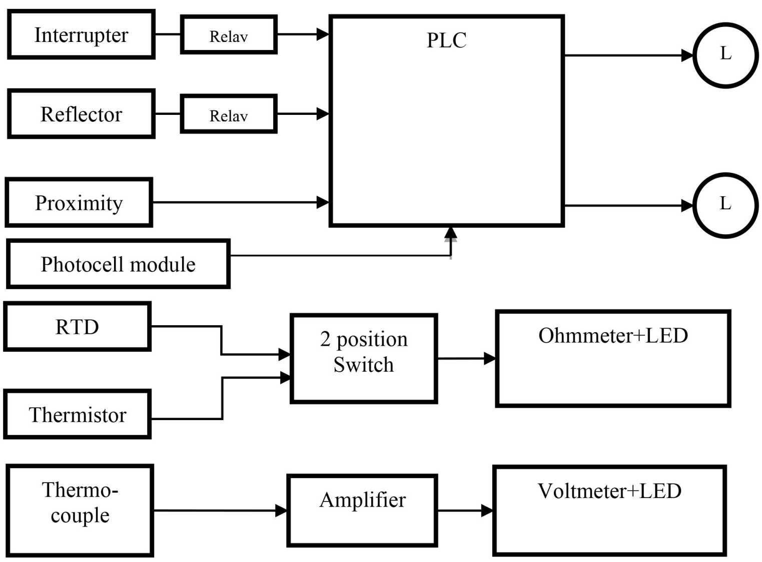


Fig. 4. Block diagram of Sensor module.

users place a metal object near the probe. When a sensor is triggered, LED 1 will light up.

Optical sensors. To use the optical interrupter, users place a thin object (such as a piece of paper) into the gap of the interrupter to block the infrared light. The interrupter operates in DARK ON mode so its output will become HIGH and LED 2 will light up.

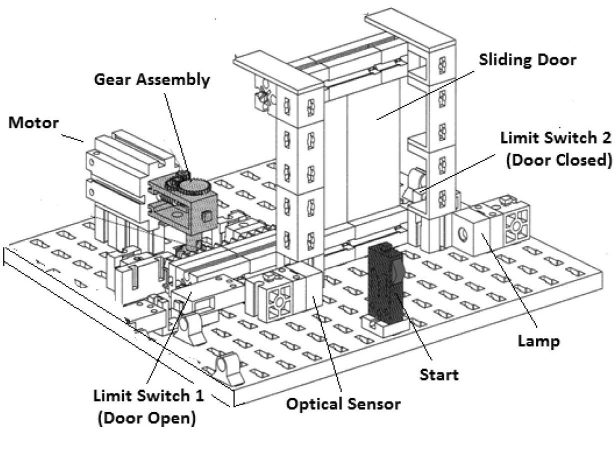
To use the optical reflector, users put a highly reflective object (such as a piece of white paper) about 3 mm above the reflector. When the object reflects infrared beam from the emitter back to the receiver, LED 2 will light up.

To use the photocell, users can block the top of the photocell with a finger; LED 2 will light up.

2.3 Automated System Module

The automated system module allows students to work with small-scale automated systems using Fischertechnik components as building blocks. Examples of automated systems include paper-drilling conveyor line, sliding door system, hand dryer machine, simplified automated storage/retrieval system (AS/RS), and automated bottle-filling station. Instructors can use this module to demonstrate the process of integrating an automated system. For example, to build a sliding door system (such as an entrance gate control system or garage door opener system), the first step is to construct a physical model. Fig. 5 shows a sliding door operated by a 9 volt DC motor and gear assembly. A switch is used to start the operation. Two limit switches are used to monitor the state (open/closed) of the door. An optical sensor and lamp assembly is placed in front of the door to check for the presence of any object in that area. A relay is used to change the direction of the motor to open and close the door. The second step, writing out the operating sequence, is also shown in Fig. 5. The third step, illustrated in Table 2, is to assign I/O ports for the input/output devices. The fourth step is to create the schematic diagram and the final step is to write the PLC program using ladder logic. Fig. 6 shows the ladder logic used to determine when to energize and de-energize the various input and output devices..

The automated system module can also be used in teaching PLC programming to demonstrate relay instructions, AND/OR logic, and timer instructions, and how to translate a sequence of operation into PLC programming. In teaching I/O interfacing, it can be used to demonstrate how push buttons, optical sensors, limit switches, and mechanical relays work; to demonstrate how MicroLogix 1000 I/O ports work; and to validate principles for wiring I/O devices to MicroLogix1000. From the system perspective, it can be used to demonstrate how to translate a conceptual design to a physical model; how to deploy sensors in different locations of the physical model for control purposes; and how to program automated systems for various applications.



Operating sequence:

1. Start button is pressed.
2. The door is closed.
3. The lamp is energized and the optical sensor is energized.
4. An object placed between the lamp and sensor breaks the light beam.
5. The motor energizes and the door slides open.
6. The door stays open for 4 seconds.
7. If the light beam is not broken, a relay is energized to activate the motor and the door closes.
8. If the light beam breaks at any time, go to step 5.

Fig. 5. Physical model and operating sequence for sliding door application.

Table 2. I/O port assignments

Input Devices	Ports	Voltage	Output Devices	Ports	Voltage
Start Button	I/2	9 Volts	Motor reverse	O/0	9 Volts
Limit Switch 1 (Door open)	I/6	9 Volts	Motor forward (24V Relay)	O/4	24Volts
Limit Switch 2 (Door closed)	I/5	9 Volts	Lamp		9 Volts
Optical Sensor (Relay 3)	I/8	9 Volts			

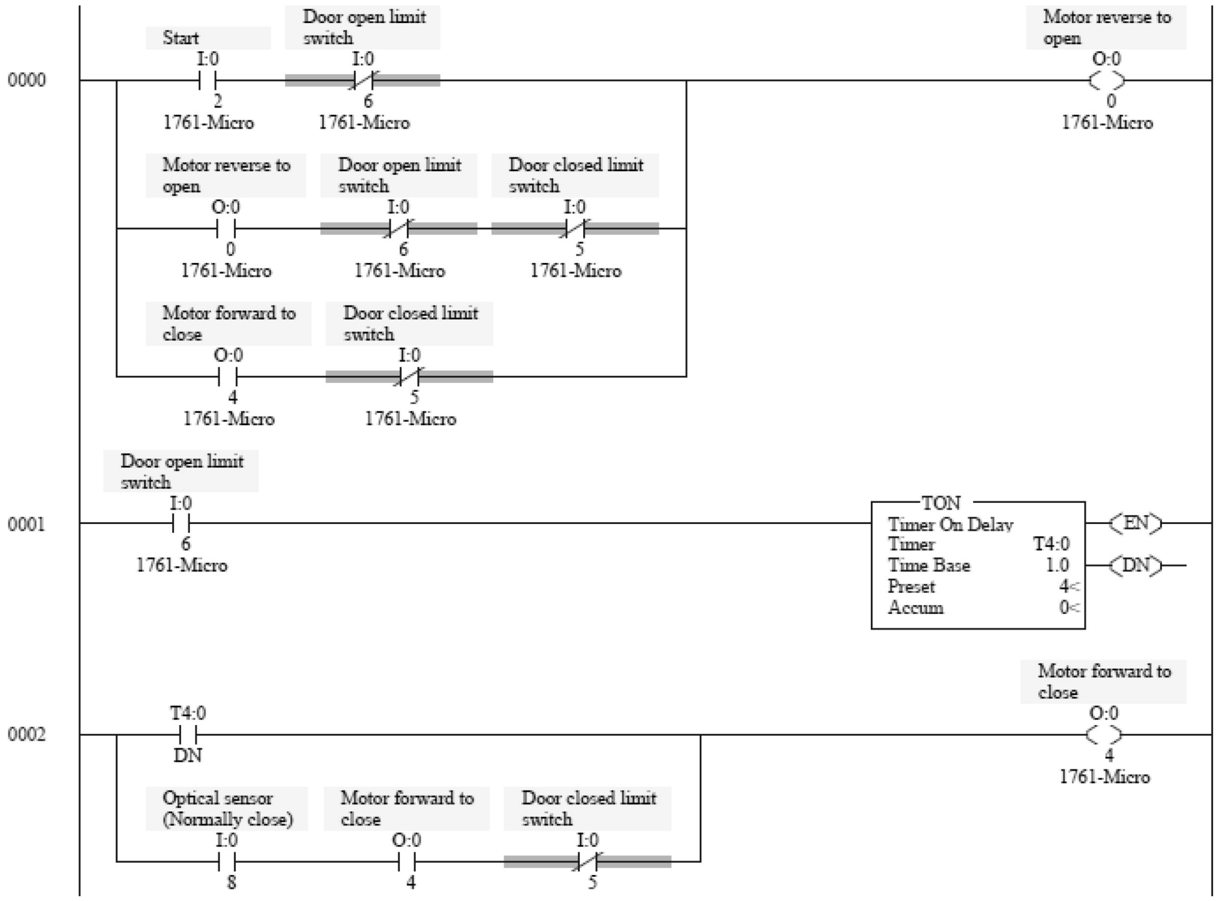


Fig. 6. PLC ladder logic program for sliding door.

Finally, advanced students can use the automated system module to design and build their own system. For safety reasons, activities related to building an automated system are performed in a lab setting because wiring is involved. Fig. 7 shows an automated system that students built to sort marbles by color.

3. Evaluation Methodology

The Basic I/O and sensor modules and the Automated System modules were evaluated separately. The objective of the evaluation was to assess students' reactions to (1) having a hands-on learning tool available for practicing PLC programming concepts while in the classroom; (2) completing an automated system design project in which the Portable PLC kit was used to build a working model of an automated system.

3.1 Basic I/O and Sensor Modules

The goal of the evaluation of the Basic I/O and sensor modules was to assess students' reactions to having a hands-on learning tool available for practicing PLC programming concepts while in the classroom.

Portable PLC kits with the Basic I/O and Sensor modules were incorporated into classroom instruction for two Automation and Robotics classes of about 40 students each. Groups of two or three students used Portable PLC units to practice concepts presented during the lectures for a period of six weeks. The instructional activities were structured based on Kolb's experiential learning theory (ELT) model, which includes four stages: (a) concrete experience, (b) reflective observation, (c) abstract conceptualization, and (d) active experimentation [24, 25]. Fig. 8 shows an example of an activity designed to help students learn how PLC Timer On (TON) instructions work. Table 3 shows how this activity addresses Kolb's ELT stages.

At the end of the six-week period, 82 students completed an opinion survey rating the following aspects of their learning experience on a 7 point Likert scale (1 = strongly disagree; 7 = strongly agree).

- The practice questions helped me learn the material.
- The hands-on experience helps me visualize the process.
- Using Portable PLC is relevant to my education.

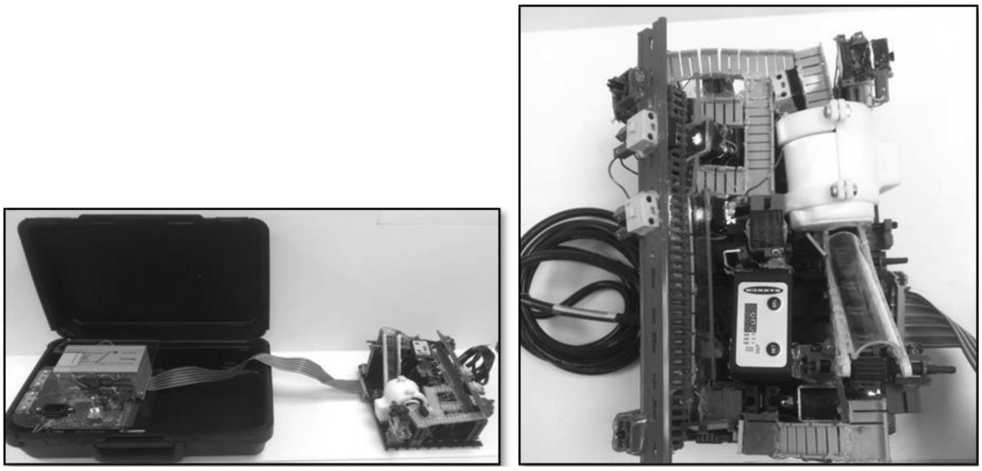
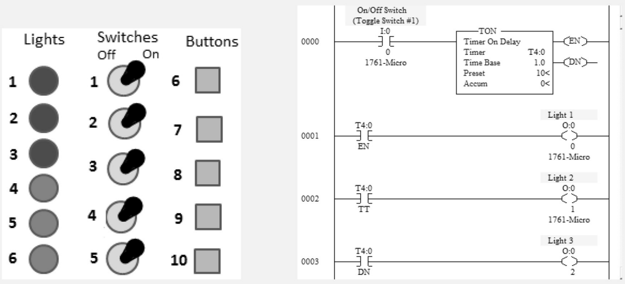


Fig. 7. Portable PLC Kit with Automated Marble Sorting System on right. The system was constructed using Fischertechnik parts and various electronic components and sensors.

Please download the TON.rss ladder logic program shown below from the PortablePLC web site. This program uses one ON/OFF toggle switch to control three lights (Light 0, Light 1, and Light 2). A TON timer instruction is used for this application. Assume that I:000/00 is assigned to toggle switch #1; O:000/00 is assigned to Light 1; O:000/01 is assigned to Light 2; and O:000/03 is assigned to Light 3. Use PortablePLC to run the program and answer the following questions.



1. *Turn switch #1 to On. Observe the states of rungs 0 and 1 and the status of light 1.*
   a. *When Accum = 0, what is the status of Light 1?*
   b. *When Accum = 5, what is the status of Light 1?*
   c. *When Accum = 10, what is the status of Light 1?*
   d. *When actual time t = 15 and the switch #1 is On position, what is the status of Light 1?*
   e. *What can you infer from the answers you have for questions (a) to (d)?*
2. *Turn switch #1 to On. Observe the states of rungs 0 and 1 and the status of light 1.*
   a. *When Accum = 5, what is the status of Light 1?*
   b. *Turn the switch to Off. When Accum = 8, what is the status of Light 1?*
   c. *Turn the switch to On. When Accum = 10, what is the status of Light 1?*
   d. *Contining question 2(c), turn the switch to Off. What is the status of Light 1?*
   e. *What can you infer from the answers you have for questions (a) to (d)?*

Fig. 8. Example of experiential learning activity designed to help students learn how PLC Timer On (TON) instructions work while using Portable PLC kit.

Table 3. Experiential Learning Theory (ELT) stages for Portable PLC learning activity

ELT stage	**Activity**
Concrete Experience	Students load and run the sample PLC program.
Reflective Observation	In Problems 1 and 2, questions a-d ask students to observe the status of Light 1 after a series of steps.
Abstract Conceptualization	In Problems 1 and 2, question e is intended to help student to form abstract conceptualizations based on their observations from questions a–d.
Concrete Experience	The assignment is evaluated. Common misconceptions are discussed during lecture. Instructor formally introduces how Timer On (TON) instructions work.
Active Experimentation	Examples will be given to test if students grasp the concept. For example, which bit would you use to turn on the output for the following problem: *After a switch is turned on, a fan goes on for 5 seconds. AC goes on until the switch is turned off.*

- I would like to have more tools like this available to help me learn.
- Using Portable PLC helps me learn more about PLC programming.

The survey also included two open-ended response questions:

- The most helpful thing about this teaching tool has been: ________
- This tool could be improved by: _______

3.2 Automated System Module

The goal of the evaluation of the automated system module was to assess students' reactions to an automated system design project in which the Portable PLC kit was used to build a working model of an automated system.

Portable PLC kits with automated system modules were used by six teams of students (two students per team) to build working models of automated systems as an optional semester project for an undergraduate manufacturing automation and robotics course. All students were introduced to the concept of an automated system and how components are integrated using animations and videos of automated systems built by previous students and by industry system integrators. With guidance from the instructor, each team decided the type of system they wanted to build. They then built their system using the following process: (1) construct physical model; (2) determine the operating sequence; (3) assign I/O ports for the input/output devices; (4) create schematic diagram; (5) write PLC program; and (6) integrate and test. Each team produced an automated system and a final report. The automated systems were evaluated based on the extent to which design goals were achieved. The final report included the outputs from each step of the process, such as photos of the physical system and PLC code, and was evaluated based on clarity and completeness.

At the end of the semester, 11 of the students completed an online opinion survey rating various aspects of their experience of using Portable PLC to build an automated system on a 7 point Likert scale (1 = strongly disagree; 7 = strongly agree).

- The project helped me to understand how automated systems work.
- The project helped me to understand how PLCs work.
- The project helped me to understand how sensors work.
- The project helped me to understand how to interface PLC with other components such as push button, relay, sensor, and/or motor.
- The project helped me to learn how to troubleshoot problems in wiring and programming of an automated system.
- The project helped me to understand how to design an automated system.
- The project helped me to understand how to build an automated system.
- I would like to have more projects like this to help me learn.
- This project was relevant to my education.

The survey also included two open-ended response questions:

- The most helpful thing about this project has been: _________
- This project could be improved by: _________

4. Results

4.1 Basic I/O and Sensor Modules

Ratings. The mean ratings on the Likert scale survey questions are shown in Fig. 9. Student

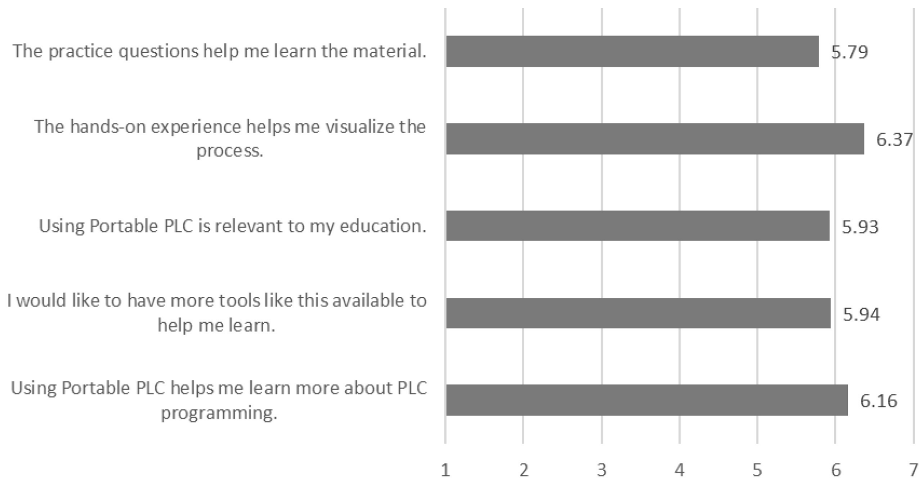


Fig. 9. Mean responses to opinion survey related to Basic I/O and Sensor modules.

ratings were positive for all items. In general, students felt that using Portable PLC and the associated practice questions helped them to learn more about PLC programming and that the hands-on experience helped them to visualize the process. They felt that using Portable PLC was useful and wanted to have more tools like it available.

Responses to open-ended questions. Students' responses to the question "The most helpful thing about this teaching tool has been:" fell into three broad categories.

(1) It helped them to visualize how the PLC works, for example:
- *You get to see it done right in front of you, and hands on visual of it helps me understand and learn better.*
- *Seeing the actual material being used and seeing everything helps to visualize the problem.*
- *Actually being able to work the system and tools physically instead of just visualizing how it COULD work. I learn quicker that way.*
- *Being able to play with the buttons and seeing the light on the portable PLC, and the programming software helps connect reality to the digital world. It is easier to grasp the concept rather than trying to visualize everything in class.*
- *Using the program with the PLC gave me a much better understanding what these are and how they work as I know several employers use these.*

(2) It allowed them to test their programs and get immediate feedback during class, for example:
- *It really helped me visualize and understand what we were actually programming. It was useful to have practice questions that are relevant and examples to real-world problems. It's definitely helpful to have a tangible tool that is affected by switches or buttons you press rather than just clicking and watching lights change on a screen.*
- *The ability to get hands-on experience and practice with a PLC and better understand how to write and execute ladder logic diagrams. Furthermore, it provides an interactive experience to the class.*
- *The hand's on PLC programming has helped me visualize how switches work. weather they are normally open or normally closed. They also are a good representation of how we will use them in the real world when figuring out the problems in lab. Hands on with the PLC's kept me interested in this class.*

(2) The opportunity for hands-on practice during class time helped them learn more quickly.
- *Having the hardware to test out the program is nice. It is easier to troubleshoot.*
- *The PLC allows us to practice the programming more than just in lab and helps us to learn because of the hands on experience.*
- *Being able to program during class is very helpful when visualizing the programs while doing homework or taking test.*

Common themes in students' responses to the question "This tool could be improved by:" included:

(1) Wishing they could check out a unit to use outside of class, such as:
- *It would have been helpful if we were able to access it when class wasn't in session. Ex - like when doing homework and want to test the circuit. I learned everything i needed about the PLC from the lab with the full size PLC. Suggest putting some in the library to be able to be checked out like a textbook.*
- *Finding a way that portable PLC's can be taken home by students so that HW can be done & tested easily at home.*
- *Making it more available at a service desk one week before the exam.*

(2) Desire for greater variety of inputs and outputs, such as:
- *More variety of outputs, not just lights.*
- *Different inputs and outputs. more push buttons.*
- *Updating the equipment w/more outputs.*

(3) Desire for more units to be available, such as:
- *Having one for everybody.*
- *You need more PLC units. I had a group of three and could never work with the PLC unit due to the fact we had to cram around one computer.*
- *Having more time and practice using it (class time is too short!)*

There were also a few comments about technical issues such as loose cable connections and switches/buttons not working.

4.2 Automated System Module

The student teams successfully built automated systems using the kits. Below are three examples of student projects.

- Automated System for Car Wash. This system mimics a real-life car washing system. The system consists of three stations: spraying bubble station, washing station, and drying station. All these stations and a conveyor system are synchronized by a programmable logic controller (PLC).
- Smart House Automated System. The system demonstrates a Smart House controlled by a

PLC. The system has three operation modes, namely, manual mode, energy saving mode, and security mode. In manual mode, the user can turn devices on or off as desired. In energy saving mode, the system can automatically turn on/off devices based on pre-determined operation rules; this is very useful in a large house. In secure mode, the system turns on an alarm and locks doors and windows when it detects an intrusion.

- Automated Sub-arc Welding System. This system automates the sub-arc welding processing by using robotics and rotating and unloading stations. An entire gantry robot system and station were built from scratch using wood. All these components are controlled and synchronized by a programmable logic controller.

Ratings. The mean ratings on the Likert scale survey questions are shown in Fig. 10. Student ratings were quite positive for all items (min 6.09, max 6.55). In general, students felt that building automated systems helped them to understand how automated systems, PLCs, and sensors work. Also, they learned how to design, build, interface, program and troubleshoot an automated system and the hands-on experience helped them to visualize the process. They felt that building an automated system was a useful exercise and wanted to have more hands-on projects like this.

Responses to open-ended questions. In students' responses to the question "The most helpful thing about this project has been:" a common theme was that the students felt that project helped them to better understand device interfacing and programming of an automated system after the subjects were covered in the class. Students noted that the project helped them to visualize course materials, to integrate the lectures with real-life learning experience, and to learn solutions that can be applied to real world problems. Below are representative responses. (Note: Interfacing devices is referred to as "wiring" but requires knowing far more than just how to connect wires.)

- *The wiring portion of the project was very useful to know. At the beginning of the project it was difficult to understand how wiring works. Now that all wiring is complete I am more confident in my skills.*
- *The hands on work, coding it by ourselves, making our own design and TA input when we had questions.*
- *I found this project to be most helpful with learning wiring and how to apply it. This also became useful when studying for the exam.*
- *Doing actual hands on work to help understand the complexity of automated systems.*
- *Setting up the wiring diagram and getting it checked by our TA and our professor was very helpful to my understanding, as well as being able to troubleshoot problems with some assistance.*
- *Was wiring and programming the PLC. Everything we learned in class we were able to apply to our project.*
- *It helped bring all the different lessons of the class together for a better understanding. Actually get-*

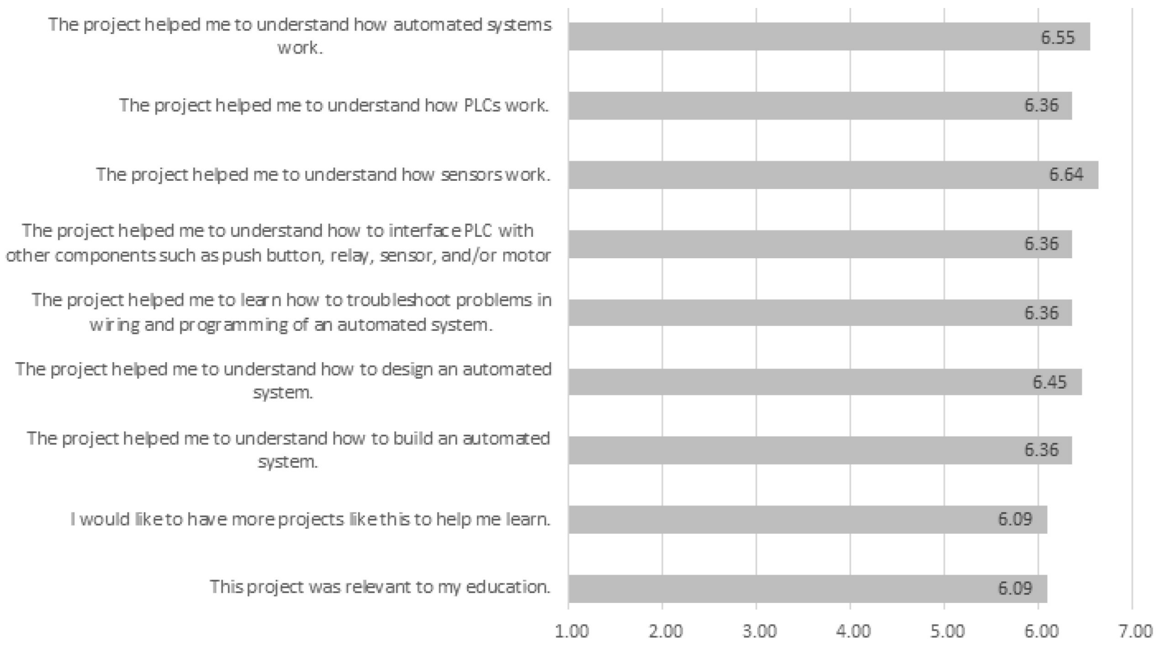


Fig. 10. Mean responses to opinion survey related to Automated System project.

ting to wire the PLC and all the components was better than any lesson I could have learned in class.
- *The most helpful aspect of this project was physically wiring all the components. Before completing this I struggled with grasping the concepts of wiring. After completing the wiring of the project I was more confident.*

In students' responses to the question "This project could be improved by:" common themes were (1) clear goals and deliverables should be communicated at the beginning of class; (2) larger work space for wiring was needed; and (3) the entire class should work on the projects. Below are their comments.

- *Providing more specific milestones throughout the project.*
- *Larger work spaces would certainly be beneficial, and covering the topic of relays and wiring at the same time as the project is being assigned would also be beneficial.*
- *Bigger work spaces for the wiring of the project. We were crowded in the lab.*
- *I think the class should be working on the project and the lessons could be taught as stages of the project.*

5. Discussion

These results suggest that the Portable PLC kits can be a useful and powerful tool for teaching PLC programming and automated system integration. Specific findings include:

- Students appreciated the opportunity to immediately practice concepts learned in the classroom, rather than wait until their scheduled lab times. Many noted that having the Portable PLC readily available helped them to visualize concepts, practice programming, and get immediate feedback – which helped them learn.
- Students wanted greater access to the kits – for example, to be able to use them at home or in a library when working on homework and studying for class.
- As students learned more about PLCs, they wanted additional features to be added to the kits, such as more types of inputs and outputs.
- Students who used the kits to build a working model of an automated system found the experience to be extremely beneficial. They were able to apply and integrate the lessons learned in class to solve a realistic and practical problem.

Limitations that may have affected the results of the evaluation include:

- The number of kits was limited. Teams of two or three students had to share a kit.
- The kits were reasonably robust, but because they were used by so many students, some maintenance was inevitably required. Making sure the kits were in good working order in time for each class was a challenge.

The kits can be used wherever PLC programming is taught, including industry training contexts. In addition, because the kit is fabricated from commercially available parts, the cost per kit is relatively low cost and the kit can be used by international as well as U.S. educators and trainers. Finally, because of their portability, the kits can potentially be used for remote/distance learning when lab access is inconvenient or unavailable, such as in rural areas or during a pandemic.

Plans for the future include:

- Build more portable PLC kits so that a lower student-to-kit ratio can be achieved.
- Continue designing in-class exercises and homework assignments that incorporate use of the PLC kits to enhance experiential learning.
- Understand knowledge gaps in building automated systems and better synchronize lectures with project milestones.
- Build more automated system modules to be used as demonstration kits so that students can see how different processes are automated and how sensors and actuators are incorporated into real-life applications.

6. Conclusion

A portable kit that allows hands-on PLC programming practice using a physical system outside the confines of a lab was designed and developed. The kit consists of a controller module and three swappable, quick connect/disconnect special function modules that can be used to teach different aspects of automation and control, including PLC programming fundamentals, sensor applications in automation, I/O interfacing, and system integration concepts. The kit was used within an undergraduate manufacturing automation and robotics course to provide students the opportunity to practice programming fundamentals while still in the classroom and for a system integration project in which students built small-scale working models of automated systems.

Evaluation results suggest that the Portable PLC kit is both usable and useful for helping students to practice PLC programming concepts. Students appreciated the opportunity to immediately practice concepts taught during lecture and to visualize results. In addition, students who used Portable

PLC to build an automated system found the experience to be helpful for understanding how to interface devices and for applying all the concepts learned in class.

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Sheng-Jen ("Tony") Hsieh, PhD is a Professor in the Department of Engineering Technology & Industrial Distribution in the College of Engineering at Texas A&M University. His research interests include engineering education; cognitive task analysis; automation, robotics, and control; intelligent manufacturing system design; and micro/nano manufacturing. He is Director of the Rockwell Automation Laboratory at Texas A&M University, a state-of-the-art facility for education

and research in the areas of automation, control, and automated system integration. Dr. Hsieh was also named Honorary International Chair Professor by National Taipei University of Technology (Taipei Tech) for his achievements in automated assembly system design, control, diagnosis and preventive maintenance (2015–2021).