

# **AC 2009-1106: AN INTEGRATED VIRTUAL-LEARNING SYSTEM FOR A PROGRAMMABLE LOGIC CONTROLLER (VIRTUAL PLC): CURRENT PROGRESS AND FUTURE DIRECTIONS**

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# Integrated Virtual Learning System for Programmable Logic Controller (Virtual PLC): Current Progress and Future Directions

## Abstract

Programmable logic controllers (PLC) are used for many industrial process control applications, such as monitoring security, managing energy consumption, and controlling machines and automated production lines. The total PLC and software market was \$7.2 billion in 2006 with steady growth expected over the next five years. Thus there is a continuing need for engineers with strong skills and knowledge in this area.

Practice is an important component of learning programming. Learning PLC programming is different from learning general purpose programming because equipment interfacing and control is involved. For example, manufacturing automation and robotics courses typically use sensors, robots, and machine vision systems—in addition to PLCs—in teaching about automated manufacturing systems. Often educational institutions lack the full range of resources needed to help students to become proficient with PLC programming. In addition, high faculty-student ratios and limitations in availability of equipment and lab time make it difficult for students to spend enough time with the equipment to become proficient.

This paper will describe activities and findings related to an ongoing NSF-funded project to design, develop, and evaluate Virtual PLC, a system that integrates multiple instructional technologies and techniques into a single Web-based learning system that is comprehensive in its treatment of PLC topics, motivational, and always available. Virtual PLC includes animations, interactive case studies, a ladder logic toolkit, and intelligent tutoring systems. In addition, we have recently developed several small-scale physical models of automated systems such as a sliding door, a temperature control, and a welding robot. These models will be used to help students to understand and debug ladder logic programs; and to introduce K-12 students to PLC programming concepts.

## Motive

Automation has a profound effect on the way we do work. The U.S. Bureau of the Census estimated that nearly \$40 billion was invested in U.S. industrial automation in 1990. In addition, across the five major industry groups that employ more than 40 percent of all manufacturing employees, nearly three out of every four plants use advanced manufacturing technology<sup>1</sup>. There has been heavy investment in the European Union and Asia-Pacific region as well<sup>2</sup>. In addition, a U.S. Census Bureau report notes that the **yearly** exports in the flexible manufacturing category (equivalent to industrial automation) were \$19.44B in 2006, a 10% jump from \$17.61B in 2005<sup>3</sup>. Moreover, **monthly** exports in the flexible manufacturing category were \$4.06B in March 2008, a 0.5% jump from \$4.04B in March 2007<sup>4</sup>. This trend is likely to continue to increase as the manufacturing sector continues to transform to a high tech, less labor-intensive and value-added industry using advanced automated systems.

In the field of automation, the programmable logic controller (PLC) is said to be among the most ingenious devices ever invented<sup>5</sup>. A solid-state control system with a user-programmable memory, the PLC is used to read input conditions and set output conditions to control machines or processes. Thousands of PLCs are used for such applications as monitoring security, managing energy consumption, and controlling machines and automatic production lines.

As an essential part of manufacturing automation, PLCs are covered in many automation and control-related courses, such as *Computer-Aided Manufacturing*, *Computer-Integrated Manufacturing*, *Industrial Control and Networking*, *Sensors and Instrumentation*, and *Manufacturing Automation and Robotics*. Students from other engineering disciplines are also exposed to PLC technology. Research by Frost & Sullivan indicates that the world market for programmable logic controllers will continue to grow, as units become smaller, more functional, and more able to work in tough environments<sup>6</sup>. The total PLC and software market was expected to reach \$8.6 billion in 2000. This indicates that there is a great need for engineers with strong skills and knowledge in this area.

Often educational institutions lack the full range of resources needed to help students to become proficient with PLC programming. In addition, high faculty-student ratios and limitations in availability of equipment and lab time make it difficult for students to spend enough time with the equipment to become proficient. Needed are web-based materials that can help overcome these barriers. This paper describes activities and findings related to an ongoing NSF-funded project to design, develop, and evaluate Virtual PLC, a system that integrates multiple instructional technologies and techniques into a single Web-based learning system that is comprehensive in its treatment of PLC topics, motivational, and always available. Special emphasis will be on newly developed models for tele-control of PLCs. Other modules will be briefly discussed as well.

## **Virtual PLC Components**

### *Animation-Based Gamex*

Gaming approaches utilizing interactive multimedia and/or simulations have been shown to be effective in improving teaching and learning of various subjects. These subjects include accounting<sup>7</sup>, decision making skill acquisition<sup>8</sup>, and engineering education<sup>9,10</sup>. Perrone et. al.<sup>11</sup> present a case study of converting a physical board game (Mr. Roger's Sustainable Neighborhood) into a medium that can be accessed via the World Wide Web. The result was very positive, preserving not only the usefulness of the board game but also increasing its accessibility.

Animation-based games are an integral part of the Virtual PLC system, as described in Hsieh and Hsieh<sup>12</sup>. For example, in teaching about PLC timer and counter instructions, here are three elements (bits) associated with each type of instruction (note: a PLC "instruction" is similar to a command in a traditional programming language). Each bit has its own unique features. Experience suggests that visualizing the bit within the context of a real-life problem helps students to learn the instruction better. In the classroom, we often demonstrate the concept by presenting a physical device and an accompanying program to control it. Students have

responded well to seeing the correspondence between the program and the external devices (input and output devices). Figure 1 shows how this approach has been implemented within Virtual PLC. The top right corner has an ON/OFF switch—representing an input device—and Lights 1, 2, and 3 below the switch represent output devices. When the switch is in the ON position and Lights 0 and 1 light up. Below the lights is the ladder logic program that is stored in the PLC processor. The first, second, and third rungs are highlighted to show that the instructions are true, and the output instructions corresponding to the output devices are highlighted. The clock needle points at 12 which is the same as the value of Accum inside the TON (TIMER ON DELAY) instruction block. The clock mimics the internal clock inside the PLC. The timing diagram on the right side of the screen shows the bit status (EN, TT, or DN). Once the ON/OFF switch is switched to the ON position; the simulation process starts. Learners can control the simulation process by using the PAUSE button to stop it or the PLAY button to continue the process. These buttons are located in between the ON/OFF switch and the clock.

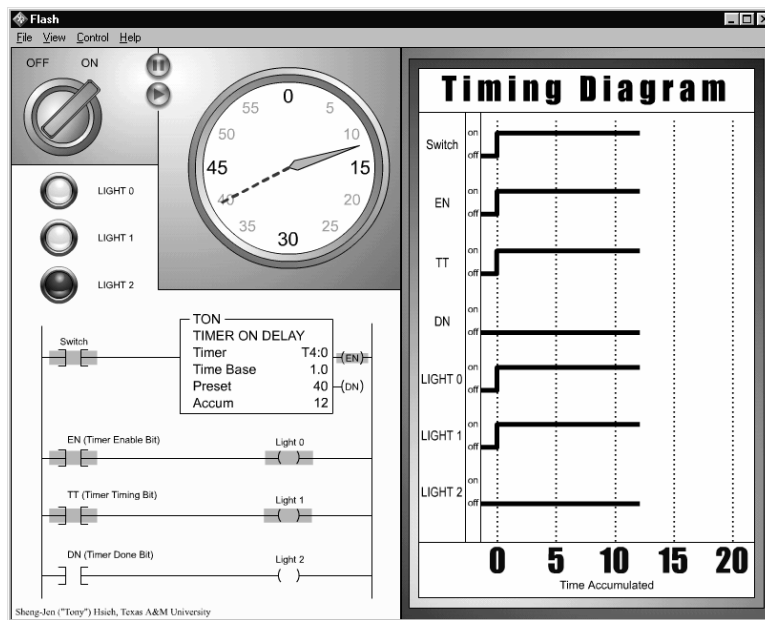


Figure 1. Simulation Based Game Design for TON instruction.

### *Ladder Logic Construction Tool Kit*

The ladder logic construction toolkit is designed to allow learners to practice building ladder logic programs. It consists of three primary components—toolbox, program structure, and control system. Figure 2 shows some screens from the toolkit. The left side of the screen contains a toolbox of instructions needed to construct a ladder logic program for a given task. The bottom right contains a program structure template.

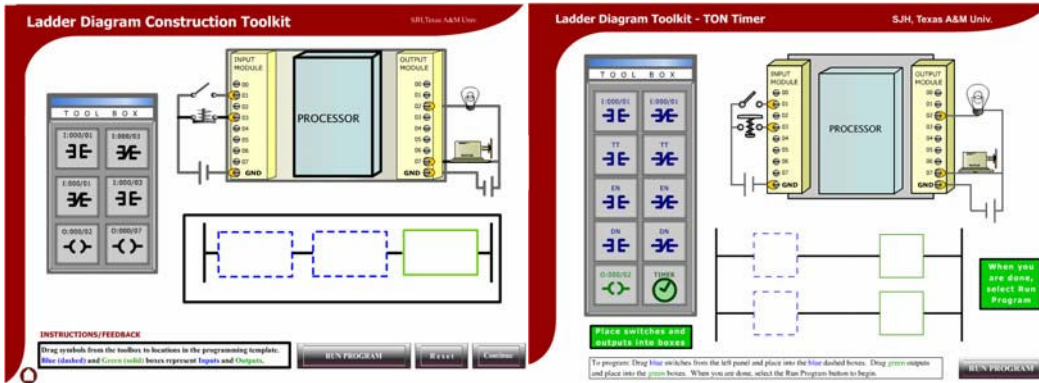


Figure 2. Outlook of the Ladder Logic Construction ToolKit.

Typically, learners (1) select a program template; (2) drag and drop instructions from the toolbox to form a ladder logic program, and (3) operate the input devices and observe the output devices to evaluate the program. Learners can also revise their programs by replacing the existing instructions with new ones from the toolbox and then run the program again until the output device behaves the they desire. Figures 3 to 6 show the transition from selecting of program template, constructing the ladder logic, to manipulating the input devices to verify the program

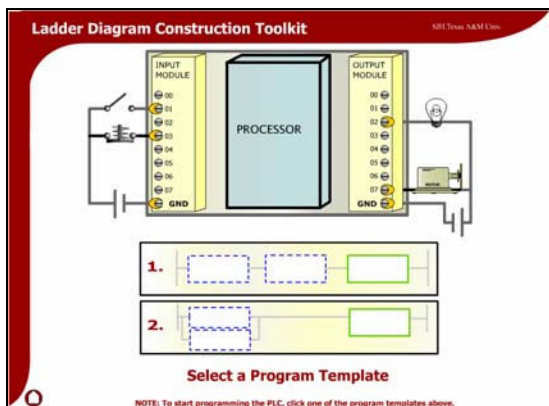


Figure 3. Template selection

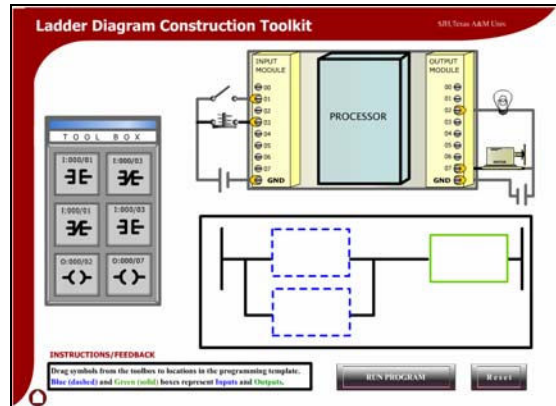


Figure 4. Parallel template is selected

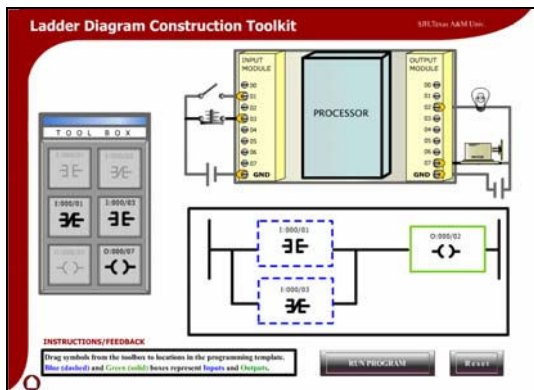


Figure 5. Ladder logic programming

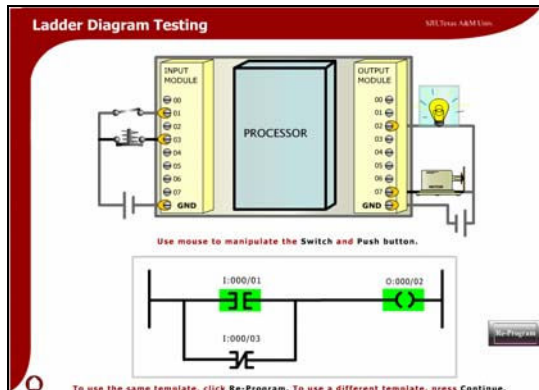


Figure 6. Ladder logic evaluation

### Intelligent Tutor for Timer and Counter Instructions

To help students learn basic information about PLC instructions, such as syntax and when to use which instruction, Virtual PLC includes intelligent tutoring system technology to provide adaptive tutorial-based instruction on timer (TON, TOF, and RTO) and Counter (CTU and CTD) instructions. Each of these instructions has several control bits that operate differently depending on the instruction. The concept is abstract and students often get the instructions and bits confused. An ITS prototype was developed using ITS authoring tool called XAIDA to test the concept and students response. Figures 7 and 8 show this system in action. However, because XAIDA is not web based, a web-based version was later developed using a similar architecture. The system has proven to be effective in teaching the concepts and is described in detail in Hsieh and Hsieh<sup>12</sup>.

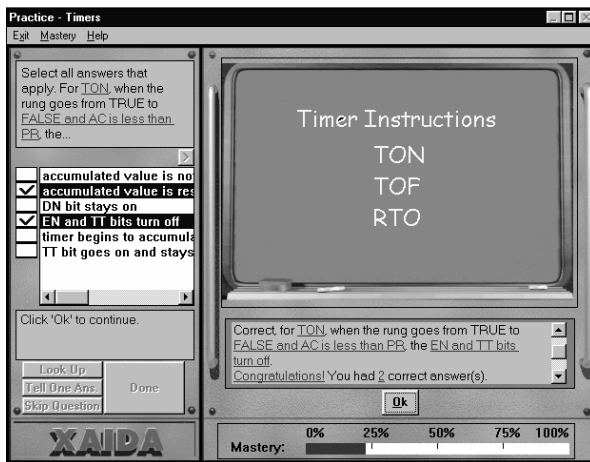


Figure 7. Practice question with feedback.

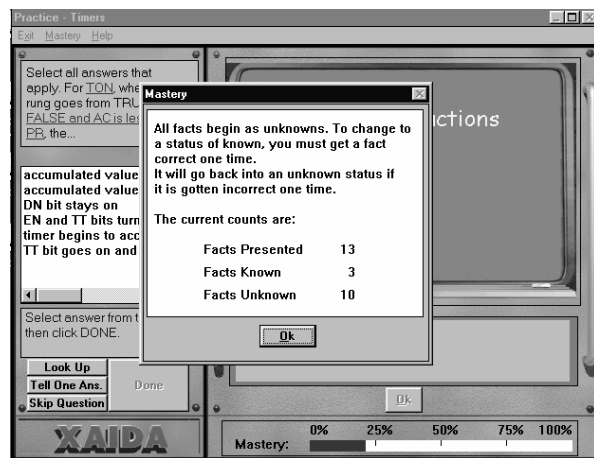


Figure 8. Summary of facts mastered.

### Intelligent tutor for ladder logic programming

The XAIDA-based intelligent tutors described above focused on teaching facts about particular ladder logic instructions. Because we believed that an additional tutor that focused on teaching students to write and to debug ladder logic programs was needed, we built an adaptive ladder logic tutor. Figure 9 shows the structure of this system. Figure 10 shows the ITS in action. The tutor has three primary components, namely, pretest and question module, individualize student model, tutor module, and post-test module.

**Pretest and question module.** The system offers a dynamic pre-test that can classify learners according to their level of knowledge, such as beginner, intermediate, or advanced.

**Student model.** The system includes an Error Patterns database that records patterns of errors in rung programming. If a learner attempts to run a program that contains an error, the system will use built-in heuristic functions to identify the error pattern in the database that most closely matches the learner's error. Once the most similar error pattern has been identified, the misunderstood concept(s) will be displayed for the learner to see.

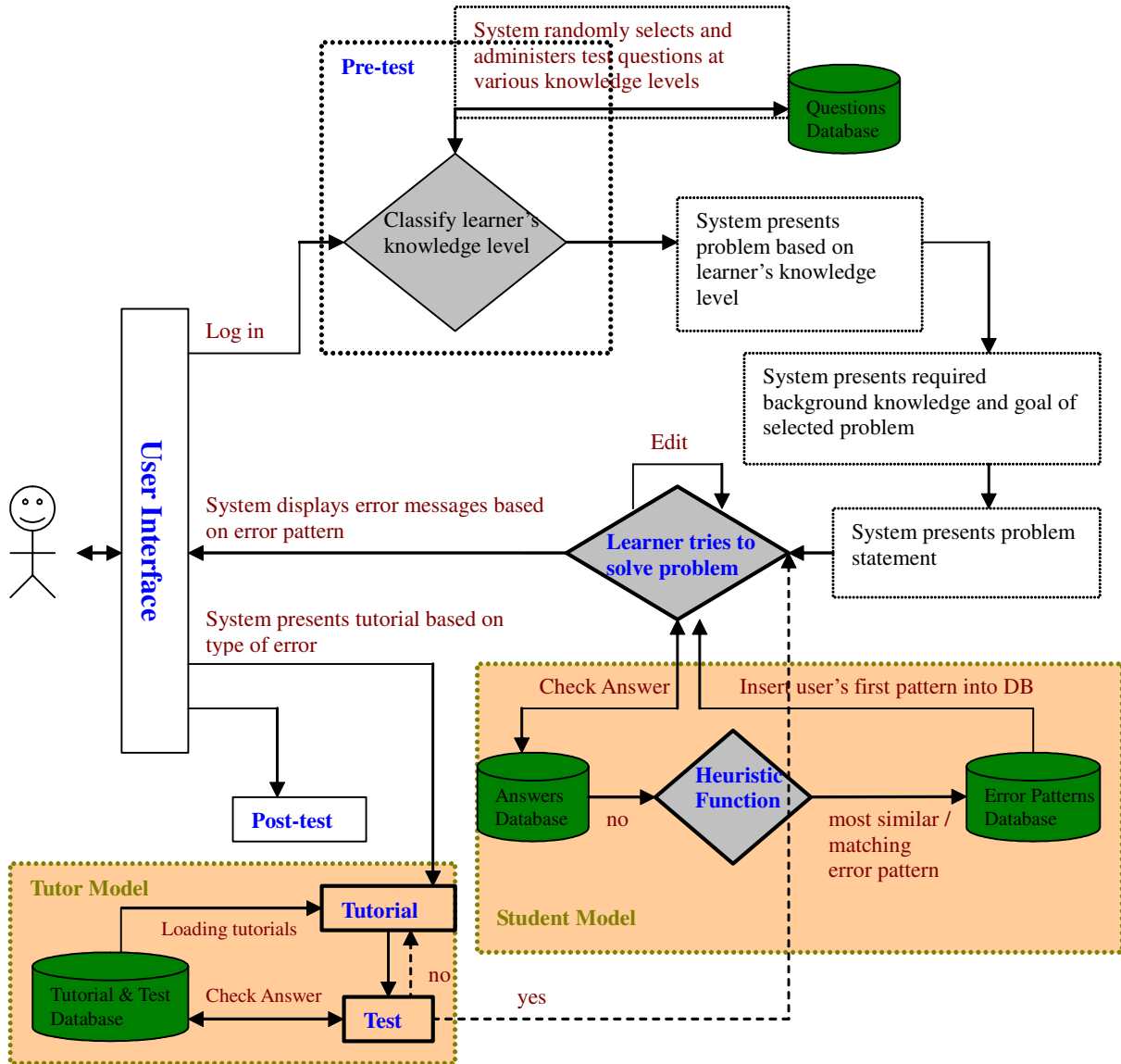


Figure 9. Structure of Ladder Logic Tutor.

Tutor model. This model addresses learner misconceptions. The student model detects any misconceptions the learner may have and informs the learner. The learner can then choose to complete a tutorial designed to address the misconception. The Tutor model will bring up the tutorials, present the concept(s), and then generate some test questions to evaluate the understanding of the learner. Once the learner has mastered the concept, he or she will be given the opportunity to try to solve the original problem again.

System adaptivity. The system is designed to continuously improve its ability to diagnose misconceptions. Whenever the learner runs a program that contains an error, the system will add the incorrect configuration to the Error Patterns database. The system will also maintain a record of the tutorials the learner chooses to complete in the course of solving each problem. Thus the Error Patterns database will gradually accumulate more error patterns and be better able to diagnose learners' errors in the future.

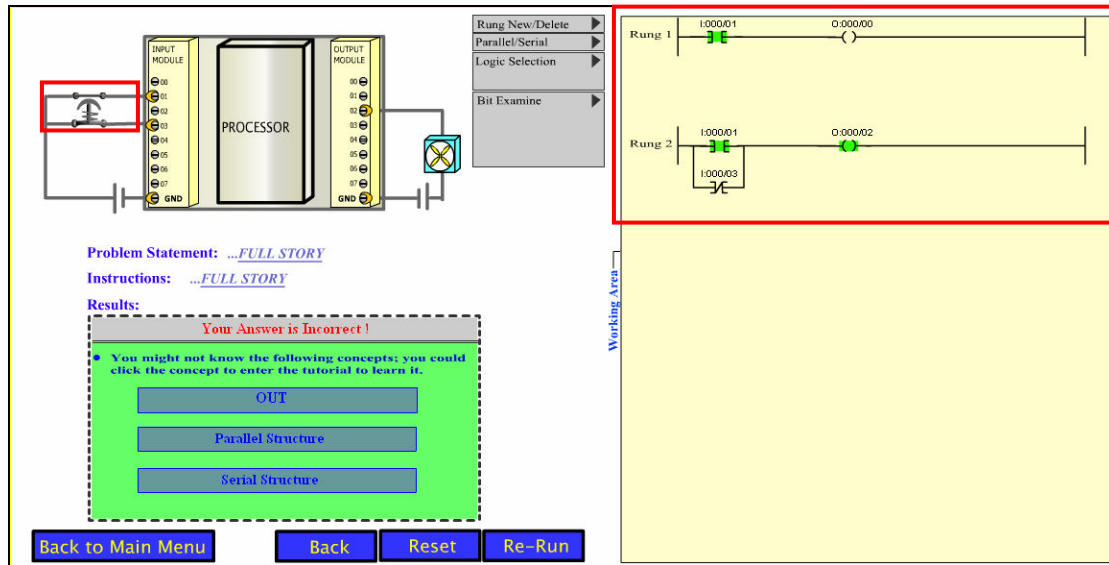


Figure 10. Screenshot of the Ladder Logic tutor in use.

### *Tele-Control of PLC Based Models*

Hands-on experience with automated systems is an effective way for students to understand and visualize how an industrial controller can synchronize all the system motions using PLC program instructions. However, real-life systems can be expensive and too big to fit into laboratory and classroom settings. Therefore, in addition to building a web-based learning environment in Virtual PLC, we also constructed realistic scale models of automated systems to help students to understand and debug ladder logic programs; and used these models for outreach to help K-12 students understand how PLCs can be used for industrial-scale applications.

A Fischertechnik Robo Starter kit was used to construct models to explain the function of PLCs in three different applications. The models were then integrated with a user interface written in Visual Basic that allows users who do not know ladder logic programming to control the models by clicking buttons on the interface. In addition, we added web pages connected to a webcam. This allows remote users to control the system and observe system functions via the webcam images. The following models have been created and are shown in Figure 11:

1. Sliding Door
2. Temperature Control
3. Welding Robot



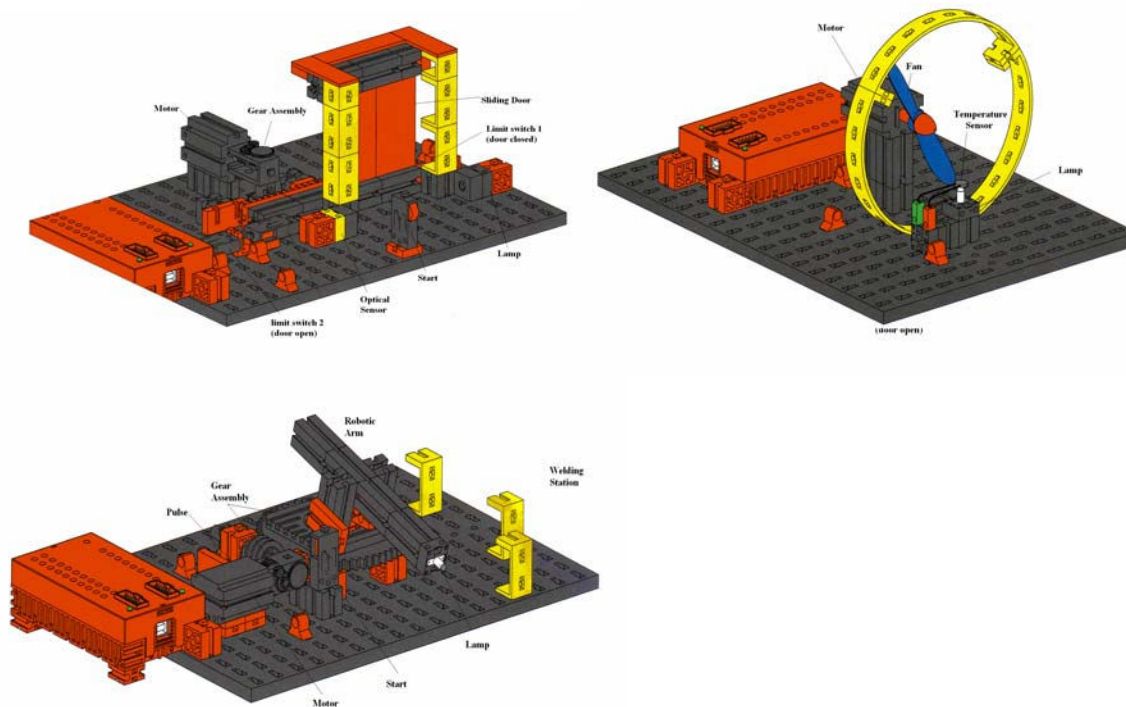


Figure 11. Tele-Control PLC Based Models.

Below we illustrate how the sliding door module works, including the sequence of events, schematics, ladder logic, VB interface design and tele-control web page interface design.

### Sequence of Events

1. Start button is pressed to start the operation.
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 door slides open.
6. The door stays open for 4 seconds.
7. If the light beam is not broken, relay is energized to reverse the motor and door closes.
8. If the light beam breaks at any time go to step 5.

### I/O Port Assignment

#### Inputs

1. **I:000/02** - Push to Start
2. **I:000/05** - Door Close Limit Switch
3. **I:000/06** – Door Close Limit Switch
4. **I:000/08** – Optical Sensor

## Outputs

1. **O:000/00** - Motor (Reverse)
2. **O:000/04** – Relay (Motor Forward)

## Circuit Schematic

Figure 12 shows a schematic of the interface between the sliding door model and a MicroLogic 1000 PLC. The MicroLogic 1000 PLC provides an internal 24VDC power supply. However, all the input and output devices—such as optical sensor, relay, and motor—require 9VDC. Therefore, a voltage regulator is interfaced to a 24VDC power supply to regulate the output voltage from 24VDC to 9VDC. Since all the input terminals require a voltage of 12VDC to 24VDC; we use three small relays to solve the power voltage requirements difference dilemma. That is, 9VDC used to drive the coil and 24VDC is connected to the contacts and the PLC input terminals. Moreover, there is only one motor to drive the door open and close. We use relays to reverse the power polarity connected to the motor so that we can reverse the rotation of the motor to open or close the door. The relay coil is driven by a 24VDC and the contacts have 9VDC to drive the motor.

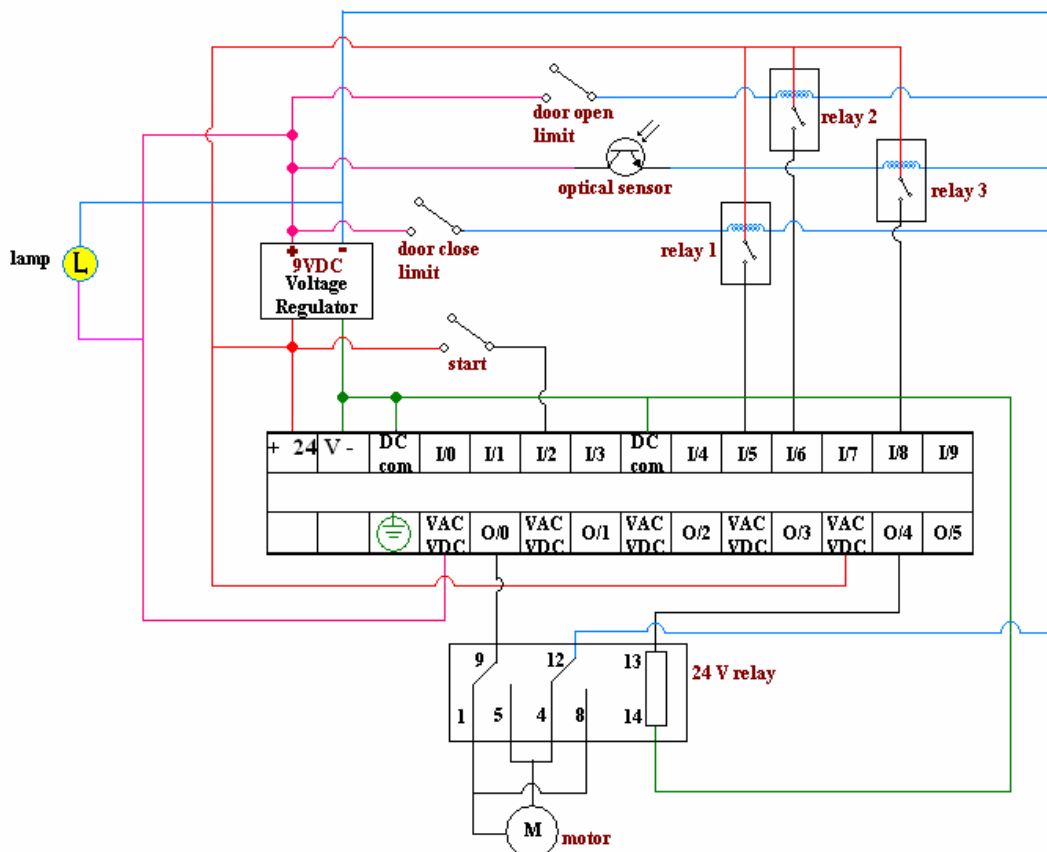


Figure 12. Schematic of Sliding Door Model Interface with MicroLogix 1000 PLC.

## Ladder Logic Diagram

We translated the sequence of events described above into ladder logic. During the process, we substituted the Input/Output devices with the given port assignments. In the ladder logic Rung #0, we use the MOV function to transfer the output O:000/00 bit status to an integer file called N7:0. Rung 1 describes the conditions in which the motor will turn clockwise to open the door. Rung #2 describes a timer TON that will turn on for 5 seconds once the door fully open limit switch is triggered. Rung #3 shows the conditions in which the door will be closed which means the motor will turn counter-clockwise. Figure 13 shows the details of the ladder logic.

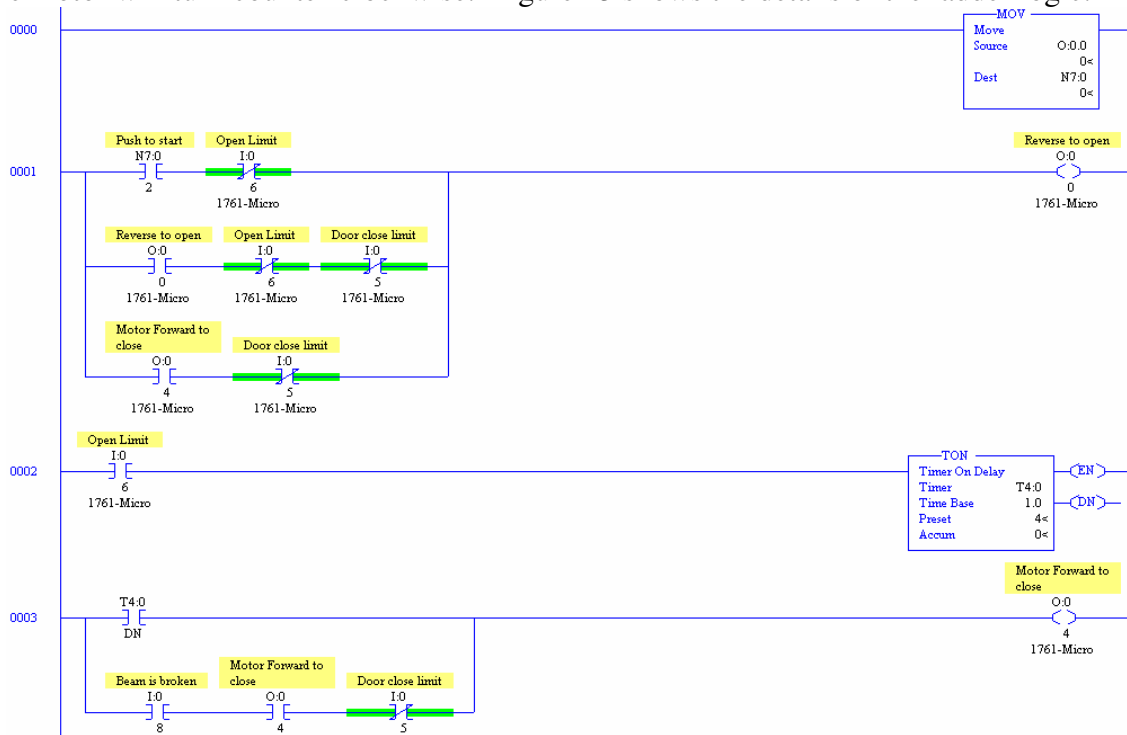


Figure 13. LadderLogic to Control the Sliding Door Model.

## Visual Basic Interface Design

As described earlier, the MOV command at the beginning of the ladder logic transfers the output bit (assigned to the motor that opens the door) status to an integer file called N7:0. A Visual Basic (VB) program with subroutines called *Unprotected Write* and *Unprotected Read* was written to exchange data with a PLC. *Unprotected Write* will write data into PLC memory and *Unprotected Read* will read data from PLC. For example, clicking on the *In-2* label (mimicking the *Start* button) on the VB user interface (Figure 13) will trigger an *Unprotected Write* function to change the status of N7:2 bit. As a result, the motor is reversed (O:000/00 – Motor is energized – Rung #1) to open to the door. Because of the MOV instruction, the O:000/00 bit status is transferred into the N7:0 file, which causes the VB program to trigger the *Unprotected Read* function to read the contents of N7:0 and change the color of *Out 0* on the interface. The output of the VB program is shown in the Figure 14 below.

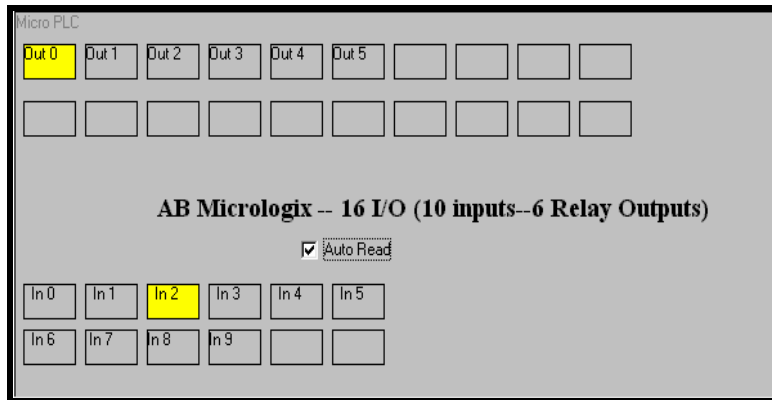


Figure 14. Visual Basic User Interface – When In2 is clicked.

Once the door is fully opened, the motor is stopped and the door stays open for 4 seconds. Then when the timer done bit is set, the relay and the motor are energized and the motor reverses (both outputs O:000/00 and O:000/04 are energized) to close the door. Once the output O:000/04 is triggered, and the *Unprotected Read* function is triggered, the output bit of O:000/04 is set to change the color of *Out 4* label on the VB interface (see Figure 15) .

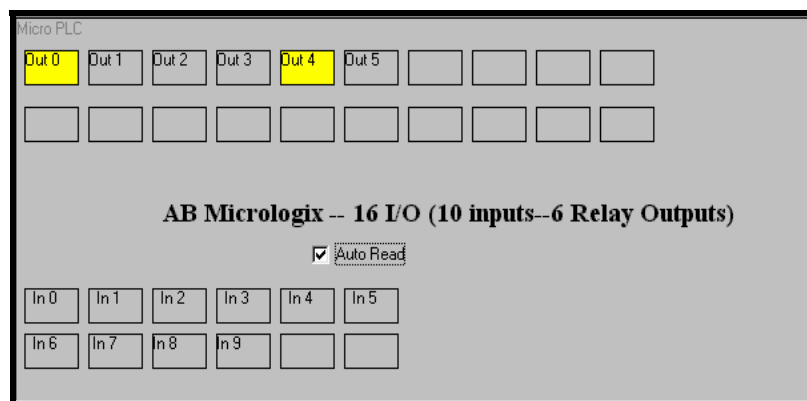


Figure 15. Visual Basic User Interface – When Motor Turns Clockwise.

If the beam of light is broken at any point by an obstruction, the optical sensor goes low and reverses the motor to open the door and the door stays open for 4 seconds after which it is closed.

### Tele-Control Interface Design

This interface provides two-way communication, allowing a user to remotely control the PLC's outputs (clicking on the *Open* button provided in the web page) as well as providing a means for the PLC to communicate its status with the user (showing the switch On/Off state on the web page). Users can view the movement of the door thru webcam.

The process is achieved starting from the PLC, data is sent through a serial connection to the server. The above Visual Basic 6.0 application, utilizes Allen-Bradley's DF1 protocol to interpret data communicated over this connection. This application provides a means for reading and writing data to the PLC's internal memory map as well as writing the status of the PLC to the server to be read by other applications.

Figure 16 shows the architecture of the tele-control architecture. Figure 17 shows the model in action through a web page with webcam presenting a live image of the model.

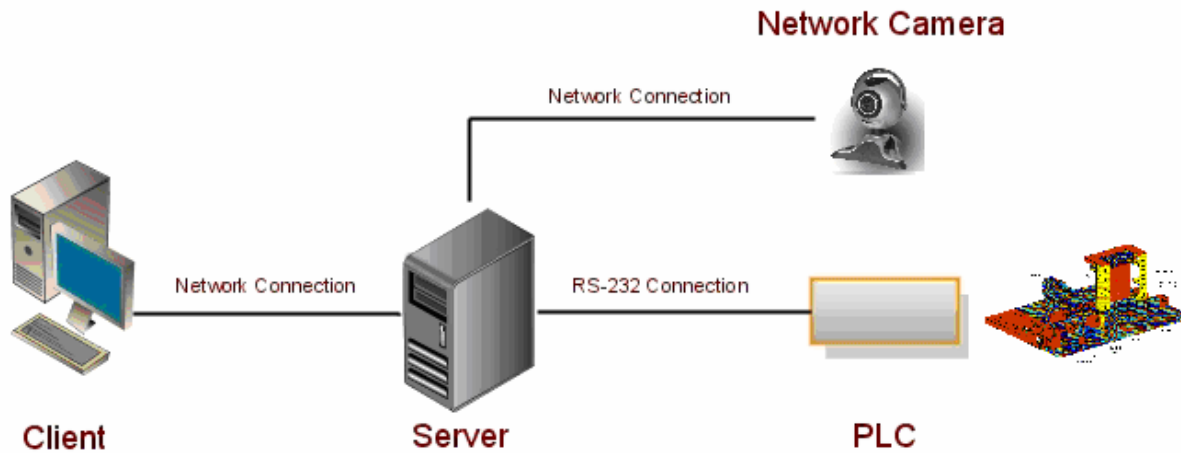


Figure 16. Tele-Control Interface Architecture for PLC Based Models.

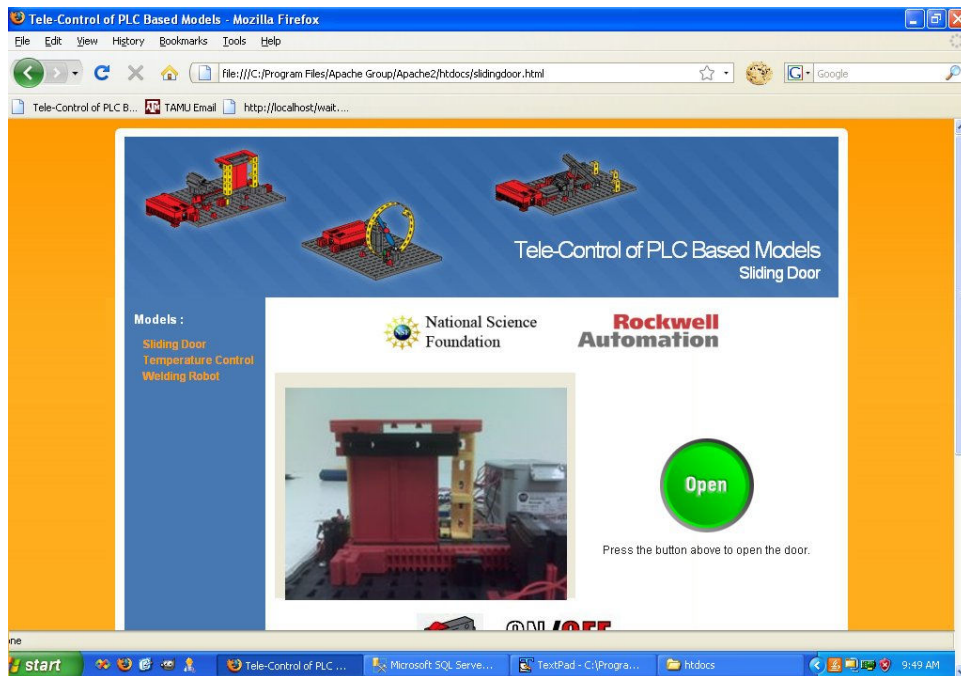


Figure 17. Tele-Control Interface Web Pages for PLC Based Models.

## Evaluation Methods

To evaluate Virtual PLC modules, an Inventory of Learning Styles is administered to understand the learning styles of student population. Then, a pre-test of the subject knowledge is administered, followed by class lectures. A second knowledge test is administered after the lectures and then students use the Virtual PLC. Finally, students take a third knowledge test and

complete an opinion survey. Figure 18 shows the sequence of the evaluation activities. Figure 19 shows sample knowledge test questions.

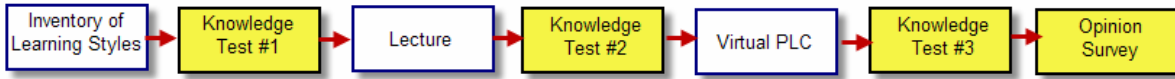


Figure 18. Evaluation event sequence.

**SAMPLE TEST QUESTION**

Select all answers that apply. A TOF instruction can be used:

- (1) for maintenance functions
- (2) in diagnostic programs
- (3) to create a short pulse at the beginning of a longer input condition
- (4) to create longer output functions derived from short input functions
- (5) to delay start of function for a defined period of time from start of some other function
- (6) to generate a short pulse at the end of a long input function

Figure 19. Sample Knowledge test questions.

The opinion survey consists of five items plus a space for comments. Students to rate various characteristics of each module on a 7-point Likert scale. Figure 20 shows survey questions for the case study module.

1. The case studies helped me learn more about PLC programming.  
*Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree*
2. I would like to have more case studies like these available to help me learn.  
*Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree*
3. These case studies were relevant to my education.  
*Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree*
4. The content of the case studies was easy to understand.  
*Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree*
5. The animations helped me visualize the process.  
*Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree*

Figure 20. Opinion Survey Questions.

## Dissemination

So far, there are 1031 registered Virtual PLC users and 12020 unique hits on the web site. As described in Figure 21, of the registered users, 34% are from Texas A&M University, 32% are from community colleges or universities, 24% do not provide an affiliation, 9% are from industry, and 1% are from international institutions.

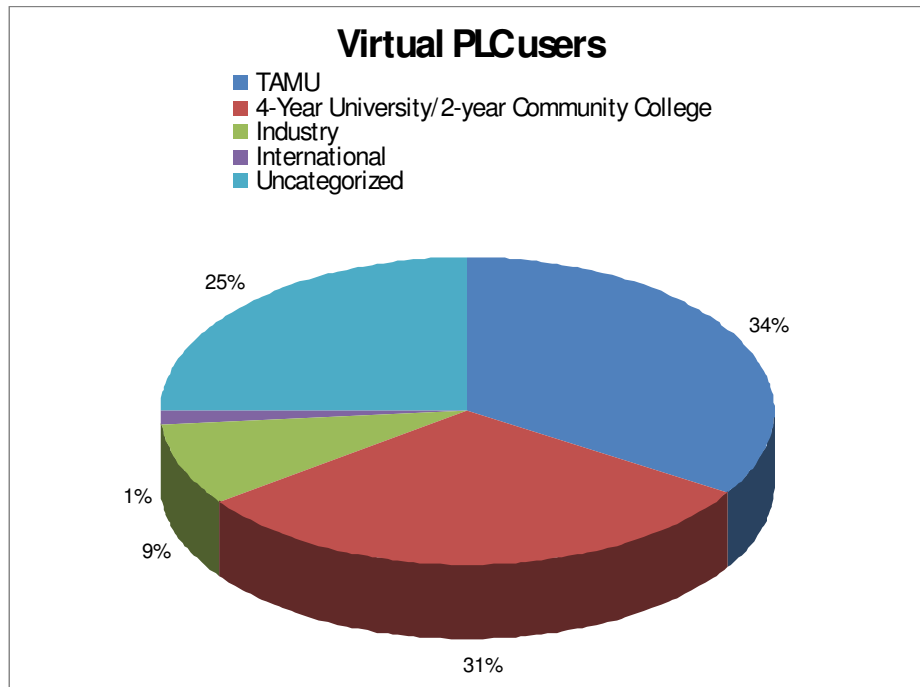


Figure 20. Affiliations of registered Virtual PLC users.

## Outreach Activities

The project team has conducted several workshops for high school students as part of Texas A&M University's outreach activities. Figures 21 and 22 are photos taken at these events.



Figure 21. Demonstration of robotic assembly line.



Figure 22. High school students exploring Virtual PLC program.

## Conclusions and Future Directions

This paper describes highlights from a project to develop Virtual PLC, a system that integrates multiple instructional technologies and techniques into a single Web-based learning system and recent work involving the development of remotely controlled PLC-based models. Future directions include full scale evaluation, holding a workshop to further disseminate the system and evaluation results, development of a video library to allow learners to see PLCs in action, and identification of a book or software publisher to aid with full-scale dissemination of Virtual PLC.

## Acknowledgments

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material are those of the author and do not necessarily reflect the views of the National Science Foundation or Rockwell Automation.

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