Design of Web-Based Ladder Logic Tool Kit
for Programmable Logic Controller Education

Sheng-Jen ("Tony") Hsieh
Dept. of Engineering Technology and Dept. of Mechanical Engineering
Texas A&M University, College Station, TX

Abstract

Labs are often an essential component in engineering education. However, factors such as limited lab time, expensive equipment and high student-to-equipment ratios often hinder students' learning. Simulation tools can be used to help prepare students to take full advantage of limited lab resources. This paper describes a web-based Ladder Logic Toolkit that provides physical and procedural simulation experiences that can help students learn about programmable logic controllers (PLCs). Students first select a programming template. Then they drag programming instructions from a tool box to the template. Finally, they evaluate program accuracy by manipulating animated input devices and observing the animated output devices. The Toolkit was evaluated by 30 undergraduate students enrolled in a manufacturing automation and robotics course. Students completed a pre-test before using the Toolkit and a post-test afterwards. Differences between students' pre- and post-test scores were significant ($\alpha = .05$). In addition, students responded positively to a survey that asked their opinions about the Toolkit's effectiveness, ease-of-use, and relevance to their education. The Toolkit has been incorporated into *Virtual PLC*, a web-based system for PLC education. Future enhancements may include the development of additional explanatory feedback for certain ladder logic arrangements and extending the programming language from ladder logic to functional block diagram.

1. Introduction

The programmable logic controller (PLC) has been described as the most ingenious devices ever invented to advance the field of manufacturing automation[1]. Thousands of these devices have been 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 Manufacturing Automation and Robotics. Students from other disciplines are also exposed to PLC technology. Research by Frost & Sullivan indicates that the world market for programmable logic controller will continue to grow as units become smaller, more functional, and more able to work in tough environments[2]. The total PLC and software market was projected to reach $8.6 billion in 2000. This trend is likely to continue to increase as the world economy grows. There is a great need for engineers with strong skills and knowledge in this area.

A goal of engineering education is to prepare students for industry by exposing them to the types of tools and equipment they will need to use on the job. Lab experiences are an integral part of

student learning process, especially within the domain of science and engineering[3,4]. Edward[5] has described the purposes of lab exercises as follows:

- Cognitive learning, which is often elucidated as the integration of theory with practice.
- Inquiry methodology, which includes hypothesis forming, experimental design and methodology and evaluation of results.
- Vocational aims, which include awareness of current practice and the inculcation of professional ethics.
- Development of personal skills, such as communications, report writing and teamwork skills.

Unfortunately, educational institutions often lack the resources needed to help students to become proficient with equipment. For example, a Manufacturing Automation and Robotics course typically uses programmable logic controllers, sensors, robots, and machine vision systems in teaching automated manufacturing system design. However, students' learning is hindered by obstacles such as:

- High faculty-to-student ratios: For example, the ratio for Manufacturing Automation and Robotics at one major university is 1:36 for lectures and 1: 18 for each of two lab sections.
- Limited lab access: Students may only use equipment during scheduled lab times.
- Limited resources to support students outside labs and the classroom: In many cases, no lab assistant support is available.
- Limited equipment to support lab assignments: Because lab equipment is often expensive, students must often work in groups. For example, an industrial scale PLC—such as an Allen Bradley RSLogix 5550 processor and a set of I/O cards—costs about $8000.

To help offset these obstacles, in recent years, a variety of computer and networking technologies have been developed. For example, remote laboratories (also known as e-Lab, Tele-Lab)[5,6], virtual laboratories[8,9,10,11], and hybrid laboratories[6] have been developed to reduce lab equipment setup costs and increase accessibility. Other developments include the use of interactive[9], multimedia-enhanced[12,13], and integrated[14] approaches and the Design-Build-Test concept[15] to make learning more interactive and visual. However, there have been relative few attempts to use technology to teach PLC programming.

The author was recently awarded a National Science Foundation grant to develop an Integrated Virtual Learning System (IVLS) for PLC education that incorporates intelligent tutoring systems, simulations, and animations. A prototype version of this system, known as *Virtual PLC*, can be found at <http://etidweb.tamu.edu/hsieh/Hsieh_VirtualPLC.html>. The design, development, and successful evaluation of *Virtual PLC* lessons on the topic of PLC timer instructions has been previously reported[16,17]. These lessons were found to be instructionally effective, and students' subjective impressions of the system were positive overall. However, the focus of these lessons was on the *usage* and *syntax* of PLC instructions.

This article describes the design and evaluation of another *Virtual PLC* component, called the Ladder Logic Toolkit. The Toolkit allows students to practice writing ladder logic statements to accomplish simple tasks such as turning on a motor. It also allows students to manipulate input

devices and PLC instructions in order to explore what happens when ladder logic is written in various ways.

2. Ladder Logic Tool Kit Design

The ladder logic tool kit was developed using Macromedia Flash. This tool allows rapid development of graphics and animations, and includes a programming language called ActionScript, which facilitates development of interactive programs and interfaces. Flash files are also quite small and can be embedded in HTML pages and accessed via the Web.

The Toolkit contains three primary components: toolbox, program templates, and control system. Figure 1(a) shows a screen shot of a Toolkit for practicing basic ladder logic programming. Figure 1(b) shows a Toolkit for practicing timer instructions.

The toolbox is on the left side of the window. It contains instructions needed for constructing a ladder logic program, such as:

- Examine On] [
- Examine off] / [
- Output energize ( )

and timer instructions such as TON (Timer-On Delay), TOF (Timer-Off Delay), and RTO (Retentive Timer On Delay).

The program template is on the bottom right of the screen. The templates reflect six common program structures (Figure 2). Instructions may be placed in series, parallel or hybrid arrangements.

The control system window is in the upper right of the screen (Figure 1). This window shows input devices (such as switches) on the left, the PLC in the middle, and output devices (such as a light and a motor) on the right. The input and output devices are interfaced with the I/O terminals of the PLC.

Students use the Toolkit as follows:

1. Select a program structure (Figure 3);
2. Drag and place instructions from the toolbox to the program structure window to form a ladder logic program (Figures 4 and 5);
3. Press the RUN PROGRAM button to run the program. Evaluate the program by operating the input devices and observing the behavior of the output devices within the control system window (Figure 6).

Students may also revise the program by replacing existing instructions with new ones from the toolbox and running the program again until the output device behaves in the desired manner.
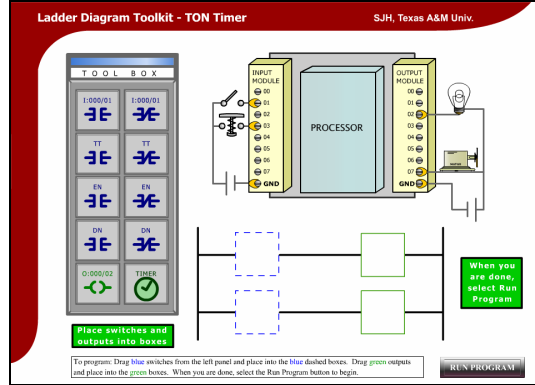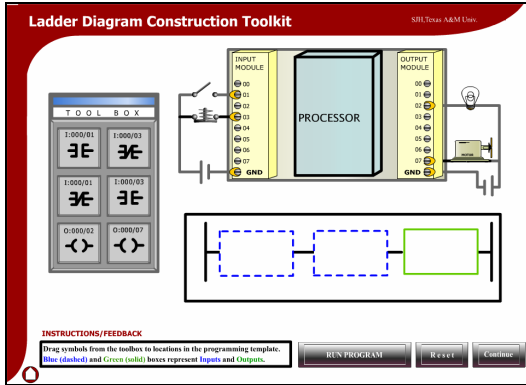
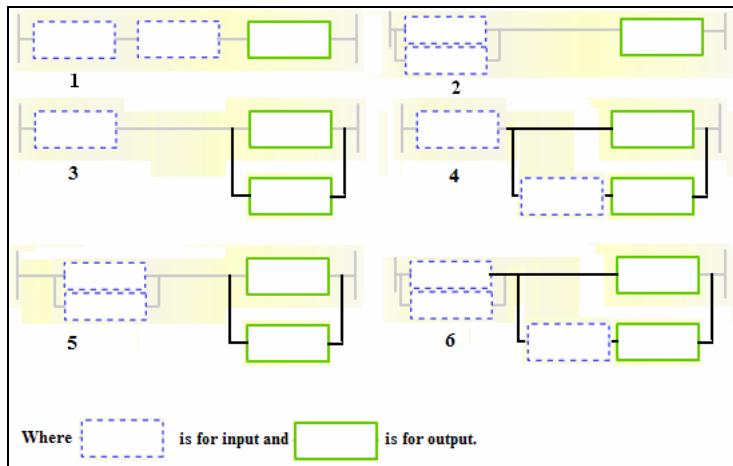Figure 1. Screenshots of Ladder Logic ToolKit.

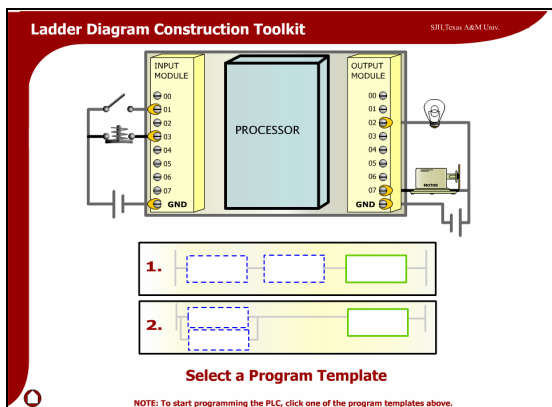Figure 2. Six commonly used ladder logic templates.

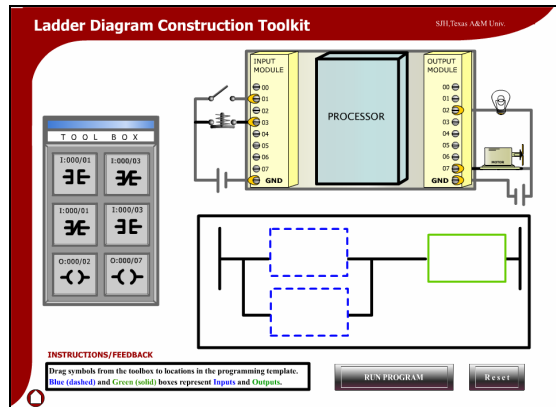Figure 3. Template selection.

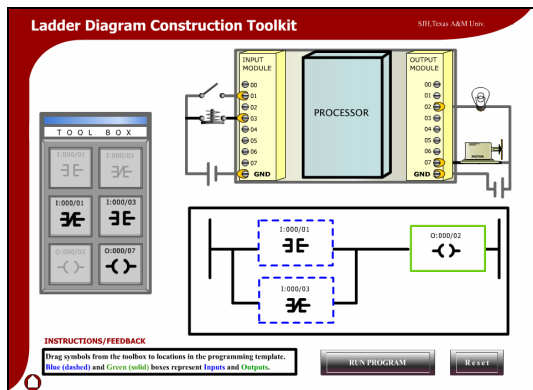Figure 4. Parallel template has been selected.

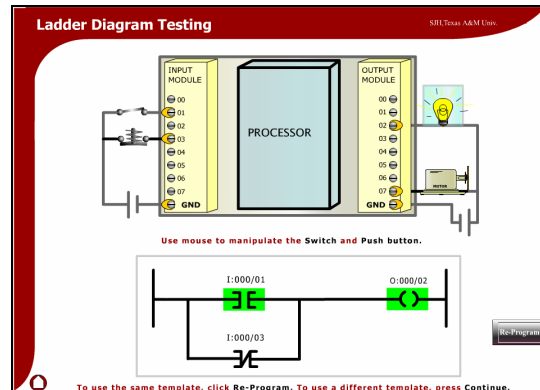Figure 5. Drag and drop ladder logic.   Figure 6. Evaluate ladder logic.

3.   Methodology

The developed ladder logic programming tool kit was evaluated by undergraduate students to
find out:

- Does the Toolkit help students to learn more about ladder logic programming?
- Student opinions about various aspects of the Toolkit, such as effectiveness, ease-of-use, and
  relevance to their education.
- Student comments

In addition, a learning styles inventory was used to find out more about these students' learning
styles in order to assess possible relationships between learning style and response to the Toolkit.

3.1   Participants, Materials, and Experimental Procedures

Participants. Participants in this evaluation were 30 undergraduate students who were learning
how to program ladder logic Input/Output and Timer instructions. Evaluation activities took
place during lab time. There were two labs of 15 students each.

Materials. Evaluation instruments included two parallel 12-item multiple-choice tests and an
opinion survey. The survey asked students to rate various characteristics of the prototype on a 7
point Likert scale. Figure 7 contains two sample questions—one from the test and one from the
opinion survey.

Felder and Soloman's Index of Learning Styles (ILS)[18] was administered to assess students'
learning styles. The ILS is a 44-question survey that asks users about their learning preferences.
The Index ranks users along four attribute continuums: Active/Reflective, Sensing/Intuitive,
Visual/Verbal, and Sequential/Global. Each attribute pair (e.g., Active/Reflective) represents
opposite ends of a 12-point scale. More information about the ILS can be found at
http://www.ncsu.edu/felder-public/ILSpage.html

Procedure. Because the instructional effectiveness of the Toolkit was unknown and because we
did not want the evaluation activities to interfere with students' learning, the unit on PLCs was
taught in the usual way with lectures followed by lab. The evaluation activities were treated as

additional lab activities. To avoid confounding learning progress obtained as a result of the lecture with that resulting from use of the prototype, we evaluated students' knowledge immediately before and after using the prototype. Figure 8 shows the sequence of the evaluation activities.

SAMPLE TEST QUESTION

Two input devices and two output devices are connected to a programmable logic controller. A normally open switch is connected to input terminal 01 and a normally open and spring return push button is connected to input terminal 03. A light bulb is connected to output terminal 02 and a motor is connected to output terminal 07. Please answer the question below based on the diagram and ladder logic given above:

1. Given the current state of the input devices, which output(s) are activated? (There may be more than one correct answer.)
    a. Light
    b. Motor
    c. Timer
    d. None of the above

SAMPLE OPINION SURVEY QUESTION

I would like to have more courseware like this available to help me learn.
Strongly disagree* 1 2 3 4 5 6 7 *Strongly agree

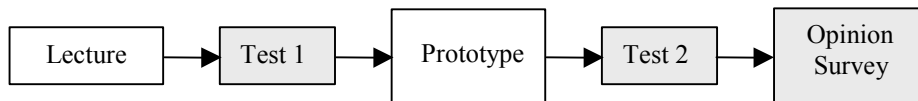Figure 7. Sample test and opinion survey questions.

Figure 8. Evaluation event sequence.

4.   Data Analysis and Results

This section summarizes the data gathered using the methodology described in the previous section. Results are presented in terms of instructional effectiveness (as measured by the two tests), student attitudes (as measured by the opinion survey), and student comments. We also briefly review the relationship between the students' responses on the learning styles inventory and their responses to the opinion survey.

Test Data. We analyzed the test data to see if there was statistically significant score improvement between tests. The null hypothesis H_o was that there would be no change. Wilcoxon signed-rank two-tailed tests were performed to compare student performance on Test 1 (after lecture, but before prototype) with Test 2 (after prototype). The analysis was performed for the Toolkit lessons on PLC timer instructions (TON, TOF, and RTO).

The analysis results revealed that the null hypothesis was rejected for all three pairs of timers instructions. This suggests that ToolKit use caused significant improvement in learning. Tables 1 and 2 summarize the test statistics, critical value and conclusions for each test, where the null hypothesis is $\mu_d = 0$, sample size was 30, and the α value is 0.05.

Opinion Survey. We also computed means for the opinion survey. Figure 9 summarizes these results. Student ratings were positive for all items. In general, students felt that the prototype was interactive, relevant, and easy to use and understand.

Learning Styles. Figure 10 shows a summary of results for all four attributes from the Index of Learning Styles for the students in this study. These data suggest that many of these students had Active, Sensing, and Visual learning styles. Figure 11 shows results for the Visual/Verbal attribute, indicating that all these students considered themselves to be primarily Visual learners. This finding is consistent with results from the opinion survey; for example, the mean response to the statement "The animations helped me visualize the process" was 5.5 out of 7.

Student Comments. Student comments can be summarized as follows: 1) Many students liked the animations; they felt being able to visualize how the program worked was very helpful. 2) Some students suggested adding sidebars to explain why certain arrangements of ladder logic instructions work (or don't). 3) Overall, students thought the lessons were helpful and supplemented the lecture well.

Table 1. Instructional effectiveness analysis results

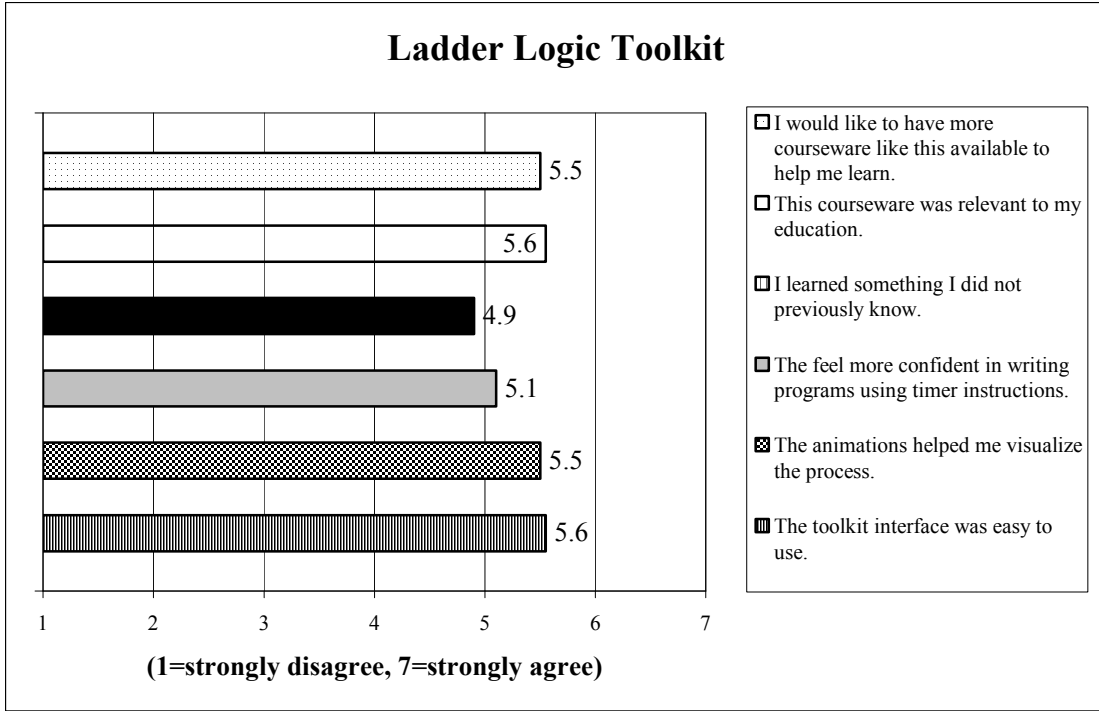| After Lecture vs. After Toolkit	Test statistic*	Critical value	Conclusion
Timer On Delay (TON) Lesson	3.91	1.96	Reject Null Hypothesis
Timer Off Delay (TOF) Lesson	2.03	1.96	Reject Null Hypothesis
Retentive Timer On (RTO) Lesson	3.81	1.96	Reject Null Hypothesis

* Wilcoxon signed-rank two-tailed test, n=30, $\alpha = 0.05$.

Ladder Logic Toolkit

Bar chart with values:
- I would like to have more courseware like this available to help me learn. — 5.5
- This courseware was relevant to my education. — 5.6
- I learned something I did not previously know. — 4.9
- The feel more confident in writing programs using timer instructions. — 5.1
- The animations helped me visualize the process. — 5.5
- The toolkit interface was easy to use. — 5.6

(1=strongly disagree, 7=strongly agree)

Figure 9. Opinion survey data.

Inventory of Learning Styles Results

Bar chart with series ACT/REF, SNS/INT, VIS/VRB, SEQ/GLO plotted against Scale (11A, 9A, 7A, 5A, 3A, 1A, 1B, 3B, 5B, 7B, 9B, 11B).

Active / Sensing / Visual / Sequential (left)
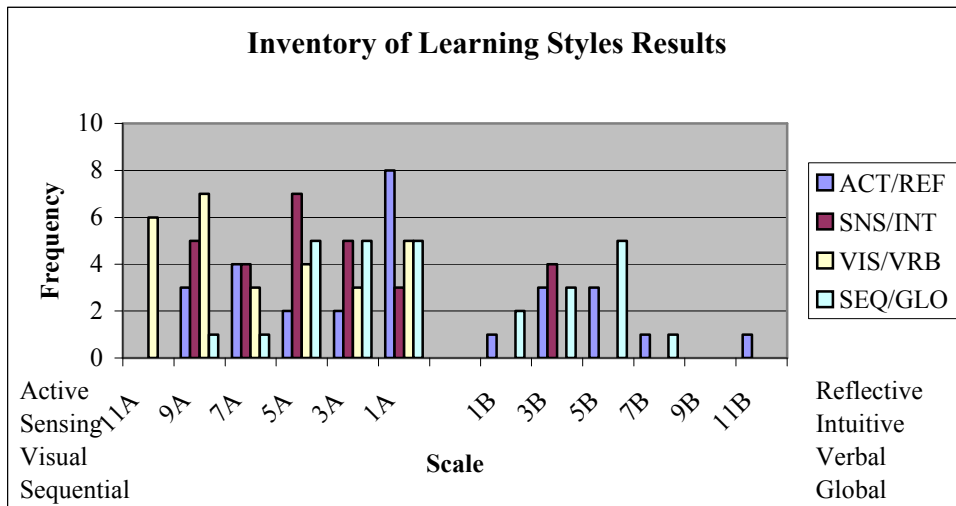Reflective / Intuitive / Verbal / Global (right)

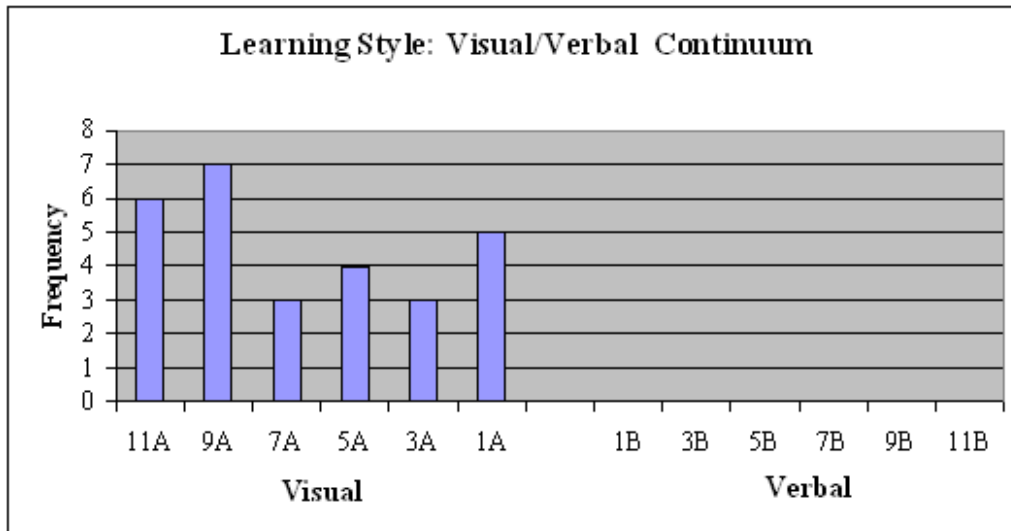Figure 10. Summary of ILS Results for Four Attributes.

Figure 11. Summary of ILS results for Visual/Verbal attribute.

5. Discussion

These results suggest that the Ladder Logic Tool Kit design is instructionally effective, and that students' subjective impressions of the system are positive. It appears that we may safely continue to develop similar types of lessons. It also appears that the Toolkit's visual, exploratory is a good fit for active, visual learners.

6. Conclusion and Future Directions

This paper has described continuing steps in the process of developing an Integrated Virtual Learning System, called *Virtual PLC*, for programmable logic controller education. So far, evaluation results have been very encouraging. Possible enhancements include the addition of more explanatory information, such as providing explanatory feedback for certain ladder logic arrangements.

More *Virtual PLC* lessons are currently under development. Future lessons will incorporate games and teaching program debugging, and programming applications such as case studies. Also, the programming language will be extended from ladder logic to functional block diagram. The ultimate goal is to create a complete system that can be used not only by undergraduate students, but also by high school students and industry professionals.

Acknowledgments

REFERENCES

[1] Asfahl, C. Ray, (1992), *Robotics and Manufacturing Automation*, John Wiley & Sons, Inc. New York, NY.
[2] *World Programmable Logic Controller Markets*, Frost & Sullivan Research Publication 5191-10 – Publication Date: January 30, 1995
[3] Surma, David R.,"Lab Exercises and Learning Activities for Courses in Computer Networks," *Proceedings - Frontiers in Education Conference*, v 1, 2003, p T2C21-T2C25
[4] Niyazov, Rafael S. Ardebili, Mahmoud K.,"Laboratory component for engineering mechanics course," *ASEE Annual Conference Proceedings, 2004*, p 8665-8670
[5] Edward, Norrie S.,"The role of laboratory work in engineering education: Student and staff perceptions," *International Journal of Electrical Engineering Education*, v 39, n 1, January, 2002, p 11-19
[6] Gurocak, Hakan, "e-Lab: Technology-assisted delivery of a laboratory course at a distance," *ASEE Annual Conference Proceedings*, 2001 p 3971-3977.
[7] Hu, Ji; Meinel, Christoph, "Tele-lab IT security: A means to build security laboratories on the web," *Proceedings - International Conference on Advanced Information Networking and Application (AINA), AINA 2004 Volume 2 (Regional Papers)*, 2004, p 285-288
[8] Bhargava, Peeyush; Cunningham, Christine; Tolomeo, Michael; Zehnder, Alan , "Virtual labs, real data for statics and mechanics of materials," *ASEE Annual Conference Proceedings*, 2003, p 9145-9150.
[9] Eckhoff, Elizabeth C.; Eller, Vicki M.; Watkins, Steve E.; Hall, Richard H., "Interactive virtual laboratory for experience with a smart bridge test," *ASEE Annual Conference Proceedings*, 2002, p 8519-8528
[10] Buehler, Dieter; Kuechlin, Wolfgang; Gruhler, Gerhard; Nusser, Gerd, "Virtual Automation Lab - Web based teaching of automation engineering concepts," *Proceedings of the International Symposium and Workshop on Engineering of Computer Based Systems*, 2000, p 156-164
[11] Allen, P.K.; Jones, T.N.; Crosby, J.P.; McCoog, P.A., "The virtual vision lab: A simulated/real environment for interactive education in robot vision," *ASEE Annual Conference Proceedings*, 1996, p 3475-3481
[12] Griffith, Michelle L.; Lamancusa, John S.; Jorgensen, Jens E.; Velez, Jorge , "Multimedia courseware to enhance the classroom experience," *Proceedings - Frontiers in Education Conference, v 3*, 1997, p 1171-1174.
[13] Crosthwaite, C.A.; Lee, P.L., "Laboratories in engineering education - the promise of multi-media," *IEEE International Conference on Multi-Media Engineering Education - Proceedings*, 1994, p 193-194
[14] Mahajan, Ajay; Walworth, Maurice; McDonald, David; Schmaltz, Kevin, "The integrated systems engineering laboratory - An innovative approach to vertical integration using modern instrumentation," *ASEE Annual Conference Proceedings*, 1999, p 5011-5019.
[15] Moor, S. Scott; Piergiovanni, Polly; Keyser, David, "Design - Build - Test: Flexible process control kits for the classroom," *ASEE Annual Conference Proceedings*, 2003, p 7361-7371.
[16] Hsieh, S. and Hsieh, P.Y., "Web-based Programmable Logic Controller Learning System," *Frontiers in Education Conference Proceedings, Boston, MA, November 6-9, 2002* (on CD-ROM).
[17] Hsieh, S. and Hsieh, P.Y., "Animations and Intelligent Tutoring Systems for Programmable Logic Controller Education," *International Journal of Engineering Education*, 19(2), 2003.
[18] Felder, Richard M., "Learning and Teaching Styles in Engineering Education," *Journal of Engineering Education*, 78(7), 674-681 (1988).