# The Development of Low-Cost Programmable Logic Controller Labs for a Control Systems Course

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**Abstract**

Many engineering disciplines require an undergraduate course in control systems, but few introduce students to programmable logic controllers (PLCs), which are commonly used to implement real-time process control in industry. Curricular exposure to PLC systems is desirable for many internship and full-time career opportunities for students studying Mechanical, Electrical or Mechatronics Engineering. Unfortunately, outfitting a laboratory with PLC systems for a few lab experiences is resource intensive and thus infeasible for many smaller engineering programs. In the area of industrial control, a single training station may cost upwards of $8000 or more. This motivates the development of low-cost laboratory experiences for teaching industrial control topics.

This paper details the development of lab apparatuses and lab documentation for several low-cost PLC labs for an undergraduate control systems course. To assess the efficacy of these labs, pre- and post- quizzes were used. In addition, students were surveyed to self-assess their understanding of and comfort with industrial control concepts. Initial results suggest that these labs effectively introduced students to PLCs, ladder logic, and pneumatic systems.

**Introduction**

Laboratory experiences are an essential part of engineering education, allowing students to gain concrete understanding of engineering concepts through experimentation on physical systems, augmented by simulation, test, and measurement hardware and software [1,2]. However, it can be challenging to fit many laboratory-specific courses into an engineering curriculum at a liberal-arts focused institution; leading faculty to adopt a mixture of in-class, virtual, take-home, or homework-style lab experiences [3]. One area where these experiences can be particularly useful is in control systems education, as students may struggle to bridge the gap between the mathematics and control algorithms and the implementation of real-world control applications [4]. In many industrial settings, Programmable Logic Controllers are used to implement real-time process control and automation, and make excellent educational tools for control systems labs [5,6,7]. Unfortunately, many PLC demonstrator platforms are expensive, costing upwards of $8000, excluding the purchase of a PLC, which may be cost-prohibitive for many small liberal arts focused institutions [8]. These factors motivate the development of low-cost laboratory experiences for engineering education.

There has been extensive research on the development of low-cost alternatives to options provided by educational supply companies [9,10,11,12]. The development of low-cost laboratory experiences can be accomplished in several ways: by modifying toys [9], modifying inexpensive systems for alternative uses [10], or by building new systems from scratch [11]. Taking the third path, the goal of this work is to present two new lab experiences for teaching PLC concepts to engineering students with bespoke demonstrator hardware. Specifically, a pneumatic system finite state machine was constructed using wood, PVC piping, valves and cylinders to translate a golf ball through a system in a continuous loop.

These lab experiences were designed with particular learning outcomes in mind. By the completion of the lab experiences, students should:

1. Gain familiarity with and experience with Programmable Logic Controllers
2. Program a PLC using ladder logic for real-time control
3. Become familiar with pneumatic systems

Direct and indirect assessment methods were used to assess the effectiveness of these lab experiences in student achievement of the learning outcomes.

This paper presents some detail on the design and development of the laboratory experiences, as well the assessment strategy and results from the pilot offering of these exercises.

## Development of Laboratory Experiences

As stated in the Introduction, the primary goals of the laboratory experiences presented in this work were to familiarize students with a PLC platform, ladder logic programming, and interaction with physical systems controlled by a PLC. Two labs were designed, one that provided a ladder logic programming tutorial followed by programming exercises, and a second which had students develop a program from scratch to control a pneumatic finite state machine.

The CLICK Plus PLC from Automation Direct was chosen as the primary hardware platform for this study as it is widely available and relatively inexpensive. The PLC system, shown in Figure 1 cost approximately $400 and possessed more than enough computational resources and input/output modules for the purpose of this work. A full Bill of Materials is available in the Appendix of this paper.

Most PLC systems come with their own proprietary ladder-logic programming software. Figure 2 shows a screenshot of the CLICK programming software used as a part of the tutorial lab. In the tutorial, students learned how to implement basic logic operations and gained exposure to PLC timers. Then, they were given three exercises to complete, shown in Figure 3, which required them to use the digital outputs on the PLC hardware.


**Figure 1:** CLICK Plus PLC used in these lab experiences

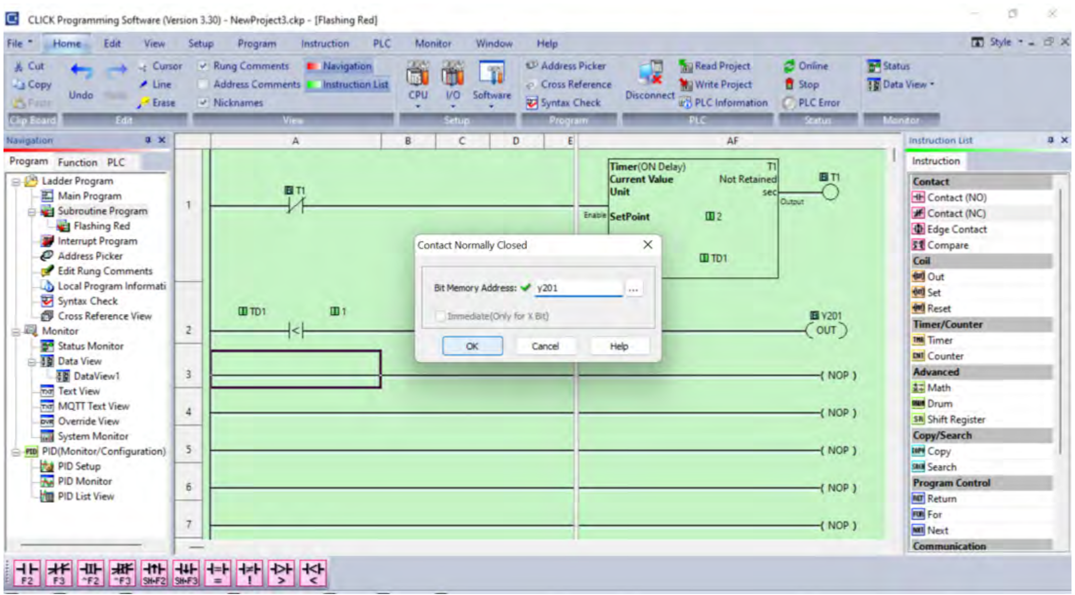


**Figure 2:** Example of CLICK PLC Programming Software

| |
|---|
| North-South see (1 second) flashing red East-West see (1 second) flashing yellow |
| North-South see (1 second) flashing yellow East-West see (1 second) flashing red |
| Standard cycle through lights every 12 seconds (Red - 6 seconds, green - 4 seconds, yellow - 2 seconds) |

**Figure 3:** Lab 1 Exercises

For the second lab experience, students used relay outputs on the PLC to control pneumatic solenoid valves. The valves were connected to a continuous loop finite state machine which passes a golf ball through a repeating circuit. The finite state machine is shown in Figure 4. In this lab students added wiring to the PLC system and used ladder logic programming knowledge to translate the golf ball using process control techniques.

In addition to lab handouts, students were provided with lecture material on ladder logic programming, PLC timers and counters, and pneumatic systems prior to Lab 1. Since these resources were provided before the lab experiences, it was possible to measure the change in student achievement of the Lab Learning Outcomes that resulted specifically from completion of the lab exercises.

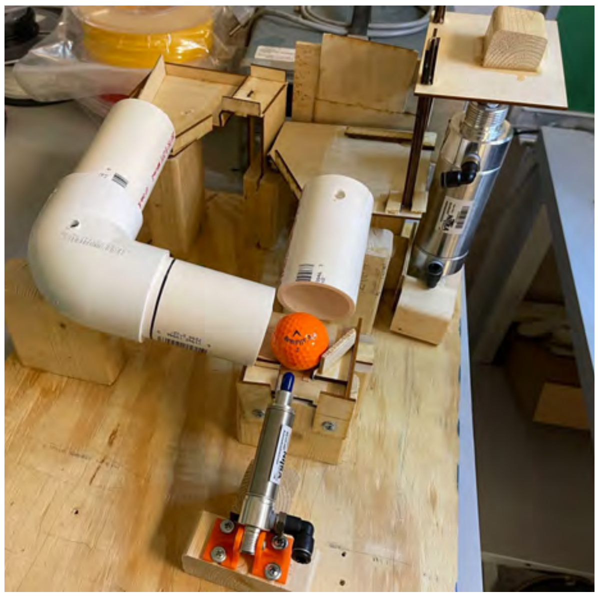

**Figure 4:** Pneumatic Finite State machine

**Assessment Strategies**

As a method of direct assessment for the lab experiences, students were given a pre-quiz before the first PLC laboratory and then the same quiz with randomized question order and randomized answer order after each PLC lab as a post-quiz. Students were not allowed to see what they had gotten incorrect on any of their previous attempts. An example of this quiz is shown in the appendix of this paper.

To indirectly assess the effectiveness of the lab exercises in helping students achieve the learning outcomes, students were asked to rate their self-efficacy in an anonymous 7 prompt Likert scale survey. The survey was on a scale of 1 (strongly disagree) to 5 (strongly agree). Specific prompts are listed in the survey results section.

## Results and Discussion

### *Pre- and Post-Quiz Results*

Online pre- and post-quizzes were utilized to measure student achievement of lab learning outcomes. Figure 5 shows the average results by quiz number, with Quiz 1 being the pre-quiz before the PLC laboratory experiences, Quiz 2 being the post-quiz after the first PLC lab exercise, and Quiz 3 being the post-quiz after completing the second PLC lab. Table 1 shows the numerical averages as well as the high and the low for each quiz. It can be seen from these results that not only did the average quiz score increase as a result of completing the laboratory experiences, but also the minimum and maximum scores increased in a similar manner. Since students were not able to see what they had done incorrectly on earlier quizzes and the questions were randomized, it is clear that students saw improvement in their achievement of the laboratory learning outcomes. The largest change was after the second lab which included pneumatics and asked students to interact with real-world systems. This suggests that pairing both an introduction to PLCs and pneumatics with a physical demonstration is significantly impactful in improving student learning.

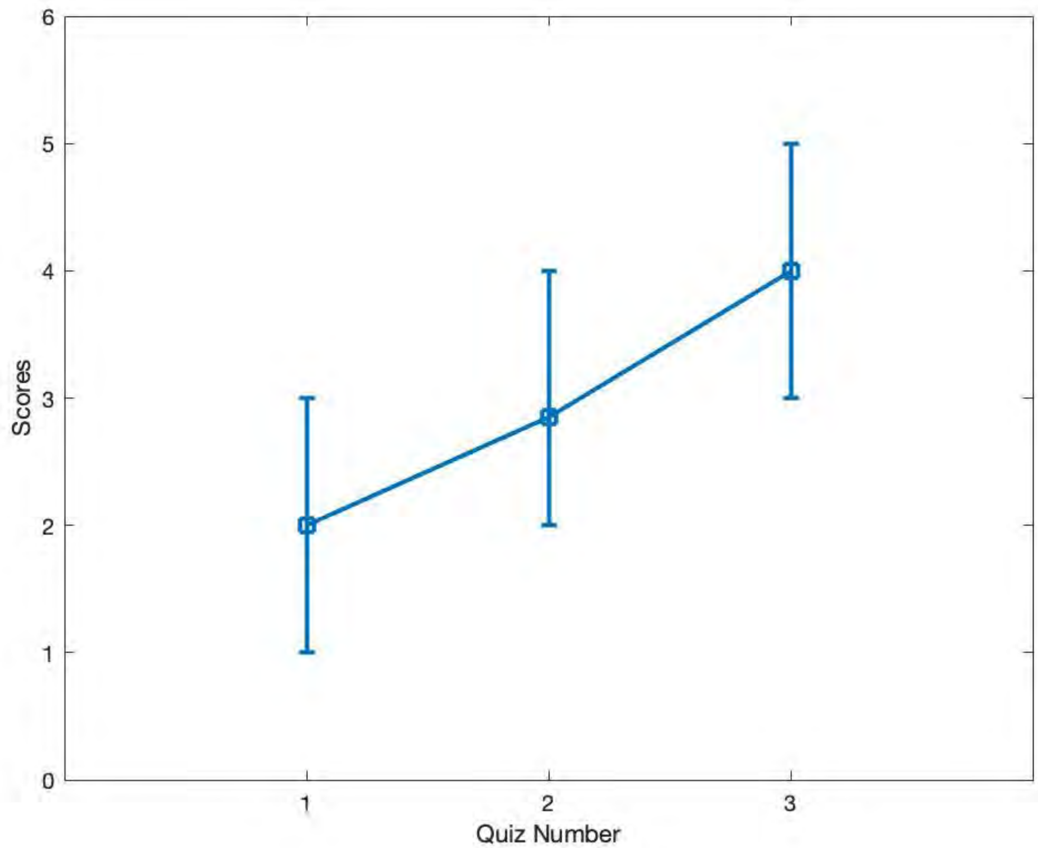


**Figure 5:** Quiz results for the direct assessment quizzes with averages and high and low scores shown

**Table 1:** Quiz results for the direct assessment quizzes

| Quiz | Average | High Score | Low Score |
|---|---|---|---|
| 1 | 40% | 60% | 20% |
| 2 | 57% | 80% | 40% |
| 3 | 80% | 100% | 60% |

***Survey Results***

In addition to direct assessment, students were asked to rate their self-efficacy on lab learning outcomes through a 7 question anonymous Likert scale survey with 5 indicating strongly agree and 1 indicating strongly disagree with the following prompts (with specific learning outcome specified for the reader):

1. I can implement real-time control on physical systems (LO2)
2. I possess a basic understanding of control for industrial processes (LO1)
3. I understand fundamentals of pneumatic systems (LO3)
4. I understand basics of ladder-logic programming (LO2)
5. I can control pneumatic actuation (LO3)
6. I feel more comfortable talking about PLCs after completing the control labs (LO1)
7. I feel that these experiences have exposed me to concepts I may see in the real world (LO1)

Table 2 shows the average response values for these questions. Of the 10 students involved in this study, all 10 completed the survey. For Lab Learning Outcome 1, students rated their familiarity with PLCs an overall average of 4.1/5 across three related questions, indicating agreement with achievement of this learning outcome. On Lab Learning Outcome 2, students rated their ability to program PLCs as an average of 3.95/5 across two related questions, corresponding with general agreement with achievement of this learning outcome. Finally, for Lab Learning Outcome 3, student responses averaged 3.65/5 across two related questions which also skews towards agreement.

Since there were only 10 students involved in this study, averages may not be the most meaningful metric for looking at the survey responses. As an alternative, Figure 6 shows a stacked bar chart which breaks down the percentage of respondents in each of the 5 categories. This is even further simplified in Table 3, which puts responses into three bins: Disagree or Strongly Disagree, Neither Agree nor Disagree, and Agree or Strongly Agree. This is useful to see that for all 7 questions, the percentage of respondents which agreed with the prompts is much higher than the percentage who disagreed. In fact, for 4 of the 7 questions, no respondents indicated disagreement. These results demonstrate that students felt like they met the Lab Learning Outcomes, which is particularly encouraging for the extension of this study.

**Table 2:** Average response values on a 5 point scale

| Question | Average | Standard Deviation |
|---|---|---|
| **1** | 3.8 | 0.92 |
| **2** | 3.5 | 0.71 |
| **3** | 3.5 | 1.1 |
| **4** | 4.1 | 1.0 |
| **5** | 3.8 | 0.79 |
| **6** | 4.3 | 0.95 |
| **7** | 4.5 | 0.53 |

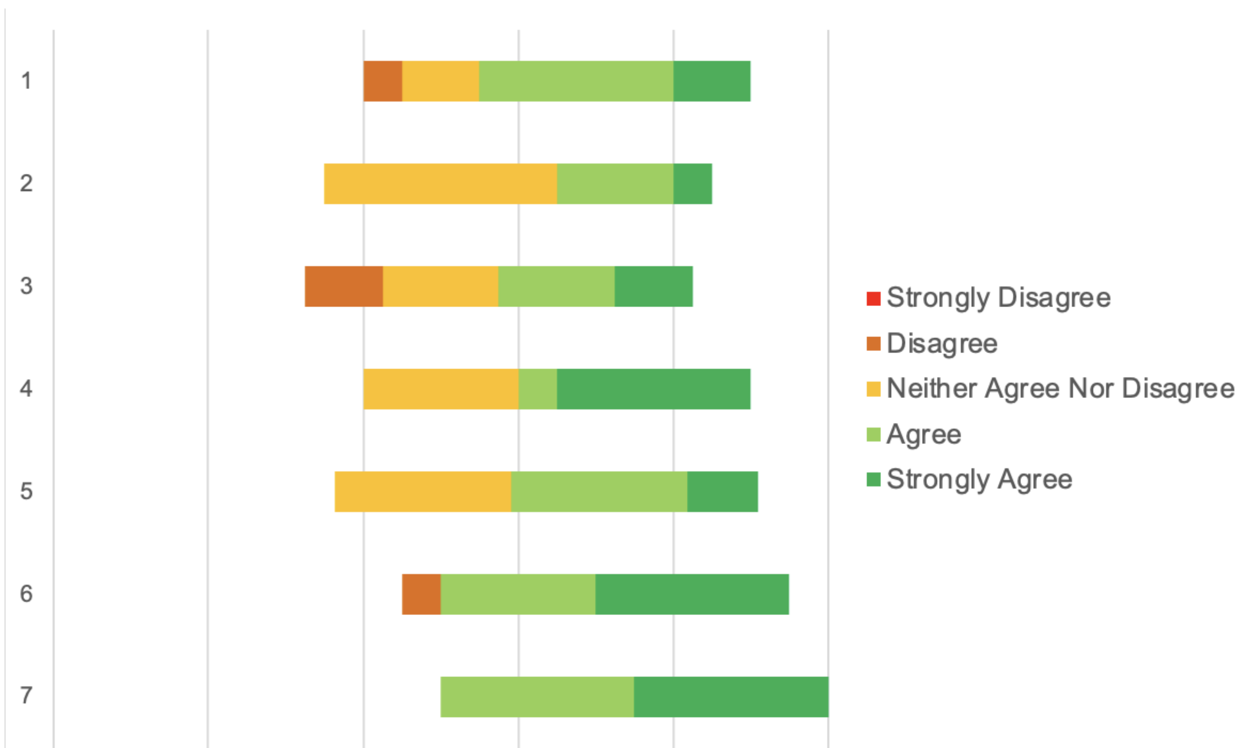


**Figure 6:** Stacked bar chart visualizing the responses to the Likert scale survey

**Table 3:** Survey responses categorized by agreement or disagreement with the prompt

| Question | Disagree or Strongly Disagree | Neither Agree Nor Disagree | Agree or Strongly Agree |
|---|---|---|---|
| **1** | 10% | 20% | 70% |
| **2** | 0% | 60% | 40% |
| **3** | 20% | 30% | 50% |
| **4** | 0% | 40% | 60% |
| **5** | 0% | 30% | 70% |
| **6** | 10% | 0% | 90% |
| **7** | 0% | 0% | 100% |

## Conclusions

The results of assessment are very encouraging for the efficacy of inexpensive lab exercises for teaching Programmable Logic Controller content to engineering students. While expensive test-beds are shiny and exciting, the measurable improvement in student understanding with much less-expensive and less-refined test beds is exciting.

Future work on this project will include refining the existing pneumatic finite state machines and adding additional laboratory experiences using a similar technique. One important additional topic, not covered in the lab exercises covered in this work, is receiving external input signals with the PLC, which was not accomplished due to time constraints on the project. This will be the top priority for the next test-bed system. Continued data collection will also benefit this work to determine if the results shown here are repeatable and accurate.

## Acknowledgements

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**Appendix**

**Table 4:** Bill of Materials

| **Part** | **Supplier** | **Cost** |
|---|---|---|
| CLICK Power Supply C0-01AC | Automation Direct | $54 |
| CLICK PLC C2-02CPU | Automation Direct | $151 |
| CLICK Discrete Combo Module C2-14DR | Automation Direct | $70 |
| CLICK Discrete Output Module C0-08TD2 | Automation Direct | $49 |
| CLICK Discrete Combo Module C0-16CDD2 | Automation Direct | $80 |
| 3/4in bore, 1/4in rod, 1in stroke NITRA A12010SP Pneumatic Cylinder | Automation Direct | $20 |
| 2in bore, 5/8in rod, 2in stroke double acting NITRA A32020DD-M Pneumatic Cylinder | Automation Direct | $93 |
| Nitra Solenoid Valve AVS-3211-24D | Automation Direct | $28.50 |
| Nitra Solenoid Valve AVS-533C2-24D | Automation Direct | $106 |
| Pneumatic Tubing | Automation Direct | $22.50 |
| PVC Piping | Lowe’s | $25 |
| Wood Pieces | Lowe’s | $25 |
| DC Power Supply (24V) | Lab Equipment | |
| Air Compressor | Lab Equipment | |
| **Total** | | $724 |

**Example Quiz (Correct Answers in Bold)**

1. What does PLC stand for?
    a. Proportional Logic Controller
    b. Proportional Ladder Controller

   c. Portable Logic Computer
   **d. Programmable Logic Controller**
2. To implement a logical AND in ladder logic put contacts:
   a. On different rungs
   b. In feedback
   **c. In series**
   d. In parallel
3. To implement a logical OR in ladder logic put contacts:
   a. On different rungs
   b. In feedback
   c. In series
   **d. In parallel**
4. How can you tell how many valve positions a pneumatic valve has?
   a. Arrows on the valve
   **b. Number of position and flow boxes**
   c. Number of ports
   d. Circuit connection symbols
5. On a PLC, input contacts are represented using
   **a. X**
   b. R
   c. Y
   d. IN
6. Pneumatic actuation is not good for:
   **a. Controlling position**
   b. Velocity control
   c. Controlling force
   d. Making good contact
7. A PLC can activate a solenoid valve using a(n)
   a. Switch
   b. Digital Output
   c. Analog Output
   **d. Relay Output**
8. Which of the following is not a function of the CLICK Programming Software?
   a. Counters
   **b. Tickers**
   c. Timers
   d. DataView
9. On a PLC, output coils are represented using
   a. X
   b. R
   **c. Y**
   d. OUT
10. A contact with a line through it is
   **a. Normally Closed (NC)**

b. Normally Open (NO)
c. Inactive
d. Active