

Design of a Virtual Laboratory for Automation Control

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Abstract

This paper presents the latest design and development of Virtual Lab, a simulation application for implementing programmable control logic (PLC) using mechanical, electrical, and pneumatic components. We developed the original version of Virtual Lab for a programmable logic controller (PLC) wiring lab in an automation and control class. While the original version of Virtual Lab received overwhelmingly positive feedback from the students and course instructor, it only contained mechanical and electrically controlled switches and it was developed using Microsoft XNA Game Studio, a game development engine Microsoft stopped supporting in 2014. The latest version of Virtual Lab was developed to expand its capabilities by including pneumatic control components using the latest game development technologies. Unity is a leading game engine with a wide range of advanced capabilities was a natural choice for continuing development of Virtual Lab. Virtual Lab now supports a wide array of pneumatic components, such as single-acting cylinder, air divider, 3/2 directional control valve, and 5/2 solenoid control valve. Other new significant features of Virtual Lab include direct 3D drag and drop manipulations of lab devices and components, more camera views (e.g., orbit tool), a more user friendly graphical interface, as well as a more realistic rendition of the lab environment. Students can now use it to perform circuit wiring for combined electro-pneumatic experiments, just like on-campus students. Classroom use of Virtual Lab has demonstrated good performance and effectiveness.

1. Introduction

Education and learning have become more accessible thanks to various online resources and technologies, such as MIT Open Courseware [1], edX (a Massive Open Online Course (MOOC) learning platform that runs on an open-source software platform (Open edX)) [2], Khan Academy [3], YouTube [4], and WebEx [5]. While online education provides many new opportunities and resources to students and professionals, one limitation of existing online education is the absence of laboratory exercises. Online educational resources often concentrate on teaching theoretical concepts, such as proving theorems or solving equations, and have very little or no coverage of practical laboratories. Laboratory experiments are an essential component of science and engineering education as they provide hands-on experiences for understanding theoretical concepts or directly addressing real world problems. Students often learn more from lab exercises than purely theoretical problems. One approach to compensate for this deficiency is to provide recorded videos of real lab experiments which familiarize students with the process of how a certain lab is conducted. However, this method alone does not adequately substitute for the physical experiment, as learners have no opportunity to practice the skills they learned from the video. Another approach that holds great potential to enhance laboratory experience for online education is the use of computer-based modeling and simulation (M&S) tools. Simulation based virtual laboratories emulate lab equipment and configurations in highly realistic 3D environments and can deliver highly effective learning experiences.

Computer-based modeling and simulation has been effectively used to model and simulate a wide range of problems in a variety of fields, with particular success in science and engineering.

For example, medical students and practitioners can safely perform surgeries on virtual patients in a simulated environment to enhance their surgical skills [6-9]. While students have traditionally prepared for laboratory sessions by reading and studying paper-based lab manuals, interactive pre-lab sessions in a computer-based learning environment offer students unique learning experiences and practical activities, while also preparing them for the physical experiment by helping them understand the experimental objectives and procedures [10-13]. Moreover, using M&S tools help to avoid damage to physical equipment and allowing learners to perform more efficiently during the physical experiment by avoiding the common mistakes made in the virtual laboratory. The rich and realistic visual effects of the virtual learning environment also make the pre-lab session more immersive and engaging.

This paper describes the software design and development of a highly realistic virtual lab for learning programmable control logic in an automation and control lab. In particular, this paper presents the latest design and development of a simulation tool, named Virtual Lab, for wiring programmable control logic in an automation and control course (MET 386 Automation and Control) offered at Old Dominion University. Virtual Lab provides distance-learning students with a realistic lab scenario and accurate simulation of Programmable Logic Controller (PLC) equipment. Before Virtual Lab, distance-learning students were required to use Computer Aided Design (CAD) software to complete their homework and lab problems which did not involve using PLCs or wire ladder logic diagrams. Virtual Lab contains mechanical, electrical, and pneumatic components that can be combined and wired to form various control logic.

The remainder of this paper is organized as follows: Section 2 introduces the real lab and a previous implementation of Virtual Lab. Section 3 describes the design and implementation of the latest version of Virtual Lab. Section 4 presents both technical results of Virtual Lab and feedback and comments from students after using Virtual Lab. Section 5 discusses future work and concludes the paper.

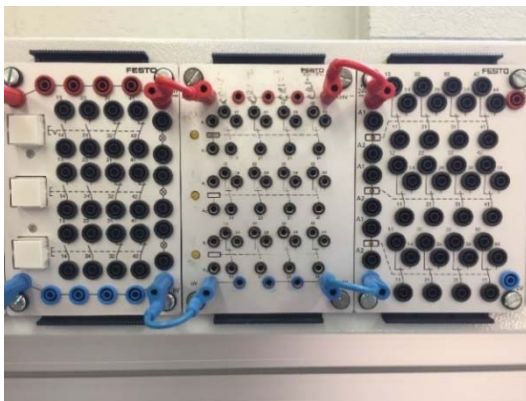
2. Background

The Mechanical Engineering Technology (MET) Program at Old Dominion University offers a course entitled MET 386 Automation and Control, which teaches the design and analysis of feedback control systems including the fundamentals of programmable logic controllers as well as practical applications of interfacing mechanical, electrical, pneumatic and hydraulic feedback control circuits. Additionally, the course has a lab section which contains: 1) four weeks of pneumatic applications, 2) four weeks of pneumatic components, electrical sensors, and ladder diagram, 3) five weeks of PLC programming [21]. A picture of the Automation Control Lab used by MET 386 is shown in Fig. 4.

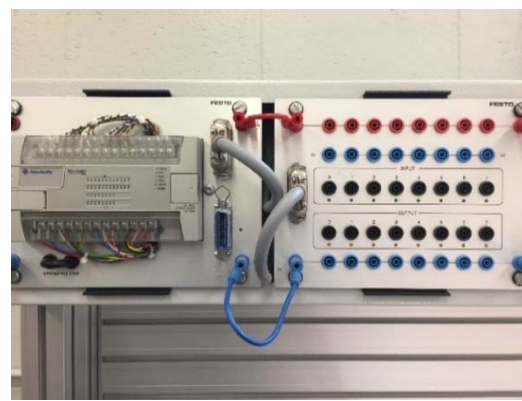


Figure 1. Automation Control Lab of the Department of Engineering Technology at Old Dominion University.

The lab contains five electro-pneumatic systems for students to conduct physical experiments. Each system consists of three major electrical components (power supply box, manual switch box, and electrical relay switch box) and nine major pneumatic components (air source, single-acting cylinder, double-acting cylinder, air divider, 3/2 pneumatic valve, 3/2 directional control valve, 3/2 solenoid (one sided) control valve, 5/2 solenoid (one sided) control solenoid valve, and 5/2 solenoid control valve. Figure 2(a) shows one manual switch box and two electrical relay switches, and Figure 2(b) shows a power supply.



(a)



(b)

Figure 2. Components of Programmable Logic Controller Wiring Lab. (a) From left to right: one manual switch box and two electrical relay switch boxes. (b) Power supply.

The first version (v1) of Virtual Lab was developed in the summer of 2013 and employed in MET 386 in the Fall 2013 semester [10]. It contained three fixed components: one power supply, one manual control switch box, and one electrical relay control switch box, Figure 3(a).

A survey was conducted at the end of the semester and received mostly positive responses from students. Virtual Lab v1 was also deployed on a tablet with touch inputs, Figure 3(b).

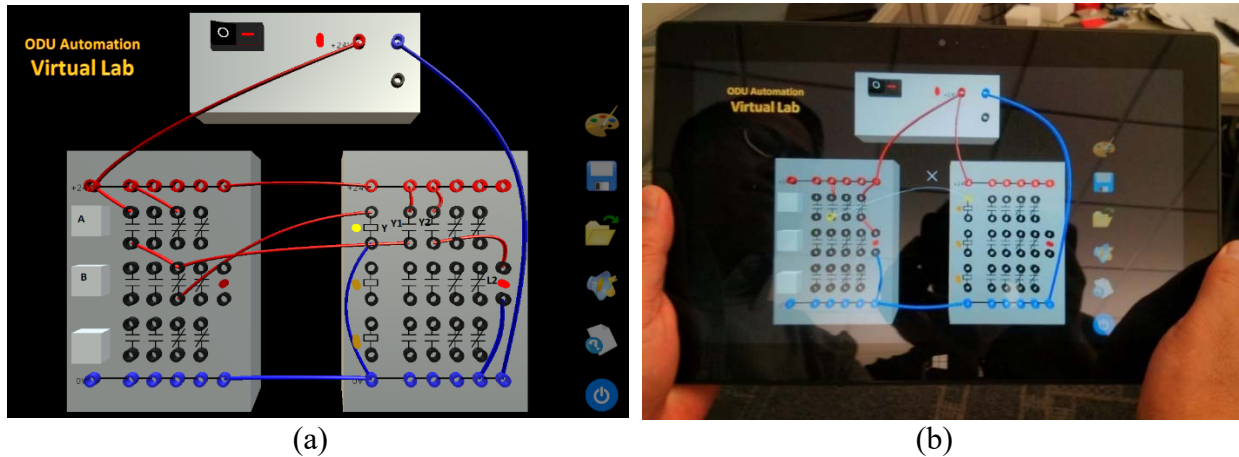


Figure 3. The first version of Virtual Lab. (a) Wiring for the memory-seal logic. (b) Virtual Lab v1 was deployed on a Windows 8 tablet.

One limitation of Virtual Lab v1 was the number and position of components was fixed. To address these problems, a second version (v2) of Virtual Lab was developed in 2014, which introduced a 2D schematic capture window (Figure 4(a)) that assists the user with selection and placement of components [11]. The 2D schematic capture was automatically converted to 3D view of the lab components. Virtual Lab v2 allowed placement and inclusion of multiple units of the same device, e.g., a student could use two manual switch boxes and two electrical relay switches in the same lab, Figure 4(b). A more standard graphical user interface with a menu bar and a toolbar was also developed in Virtual Lab v2, increasing user options such as the number of colors for wiring.

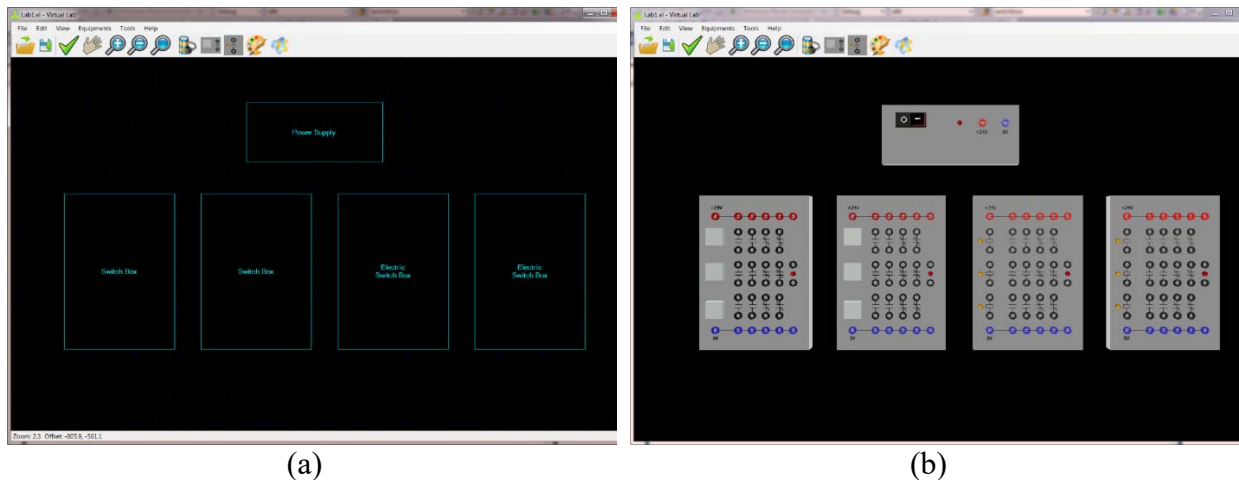


Figure 4. The second version (v2) of Virtual Lab. (a) 2D schematic capture. (b) A lab that contains multiple units of the same device, e.g., two manual switch boxes and two electrical relay switches.

3. Design and Implementation

The first two versions of Virtual Lab only contained mechanical and electrical components and lacked the pneumatic components used in the real physical lab. In addition, both versions were developed using Microsoft XNA Studio, for which Microsoft discontinued support in 2014. The development of Virtual Lab continued in 2017 using Unity, which is a leading game engine for developing cross-platform games and applications. Figure 5 shows the application architecture of the latest version of Virtual Lab.

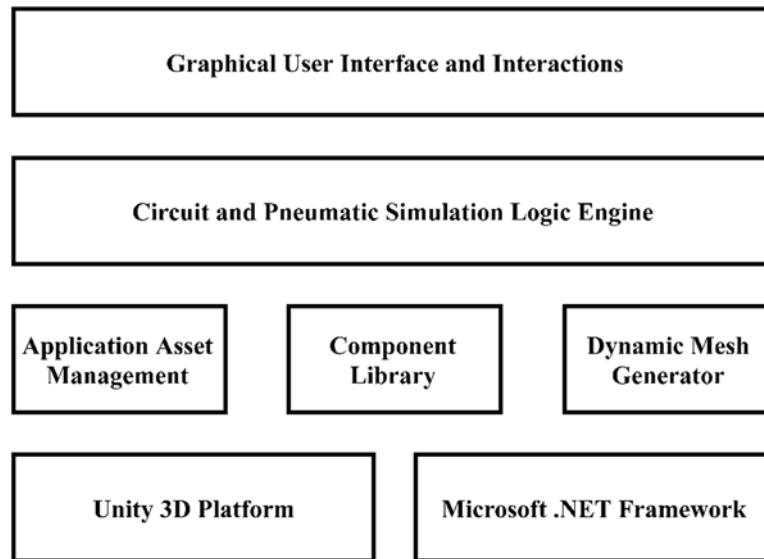


Figure 5. Virtual Lab Application Architecture.

The major software components utilized by or developed for Virtual Lab are as follows.

- **Unity 3D Platform** is a cross-platform game engine developed by Unity Technologies. It provides a comprehensive set of powerful capabilities, including a visual editor, a graphics rendering engine, a physics engine based on Nvidia's PhysX, multiplayer and networking, audio, animation, cinematics, user interface, navigation and pathfinding, virtual reality, and augmented reality. Unity is the most popular game engine in the world and it does not charge royalty for games or applications developed using Unity.
- **Microsoft .NET Framework** is a software framework released by Microsoft for fast application development for Microsoft Windows platforms and other platforms. It contains a common runtime engine shared by all .NET-aware languages and a base class library that provides comprehensive functionalities and services. Several classes and types provided by the .NET Framework such as List and Dictionary are used extensively in Virtual Lab to provide basic data structures and algorithms. Serialization and deserialization services provided by .NET Framework are used to implement file operations.
- **Asset Management** contains and manages all the digital assets used in Virtual Lab, including raw 3D models, 2D image textures, materials, modified prefabs, and sound effects. Most of the 3D models are pre-processed into modified prefabs to facilitate reuse.

and improve efficiency. Moreover, this paper developed a custom mesh generator in Virtual Lab for generating dynamic meshes.

- **Component Library** contains both graphical models and behavior models of the components used in Virtual Lab. It contains 3 electrical components and 11 pneumatic components. A large set of classes was developed to represent and manage different components. Furthermore, software reuse techniques such as inheritance and containment have been heavily utilized in building the component library.
- **Dynamic Mesh Generator** is a vital component in Virtual Lab, as it creates a dynamic tube-shaped mesh representing the wire or air tubes used to connect different connectors on the equipment in Virtual Lab. There are two types of geometrical objects used to display the wires. After the user selects the two connectors (nodes) from the equipment, an adjustable curve is formed and rendered by the movement of the cursor. This adjustable curve is a simple polyline generated using Hermite curves. When the user clicks the mouse left button, the wire location is finalized and becomes a thick wire object. The thick wire object is represented by a triangle mesh that is generated by extruding the Hermite curve from the center. Caution was taken to generate a surface tube that is smooth without gaps.
- **Circuit and Pneumatic Simulation Logic Engine** provides the core simulation engine for the programmable logic controller in Virtual Lab. The most critical component in the circuit simulation engine is a node that represents a connector (or terminal) in the equipment. Each node includes three states based on its current voltage: Positive, Ground, and None. The topology of the electro-pneumatic connection is determined and updated based on the generated wires and the status of switches. The nodes states are then updated according to the current electro-pneumatic topology. The final simulation outputs are in the form of LED lights and piston positions that are updated based on the states of nodes.
- **Graphical User Interface and Interactions** provides the user interface (UI) and handles user interactions. It contains a simple menu system that allows the user to select, place, move, or delete components and displays help information. The application has its own proprietary file format to store lab configuration and wire connection data. Common file operations include New, Open, and Save functions. The major user interactions are placement of lab components and connection of wires or air tubes between components. Users can pan, orbit (within 180°), and zoom the entire lab scene.

The software components in upper layers of the software architecture shown in Figure 5 utilize software components in lower layers, via general object-oriented programming or game object components in Unity.

4. Results

This section shows a few example lab configurations in Virtual Lab along with validation and student survey results from Fall 2017 semester.

Figure 6 shows an AND gate control logic: when button A and button B are being pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

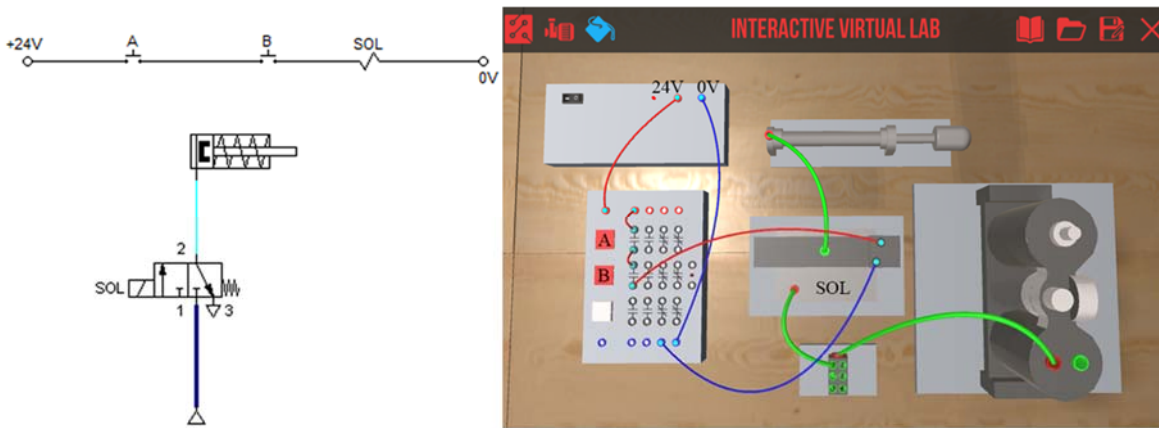


Figure 6. AND Gate Ladder Diagram and Wiring Validation.

Figure 7 shows an OR gate control logic: when button A or button B is being pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

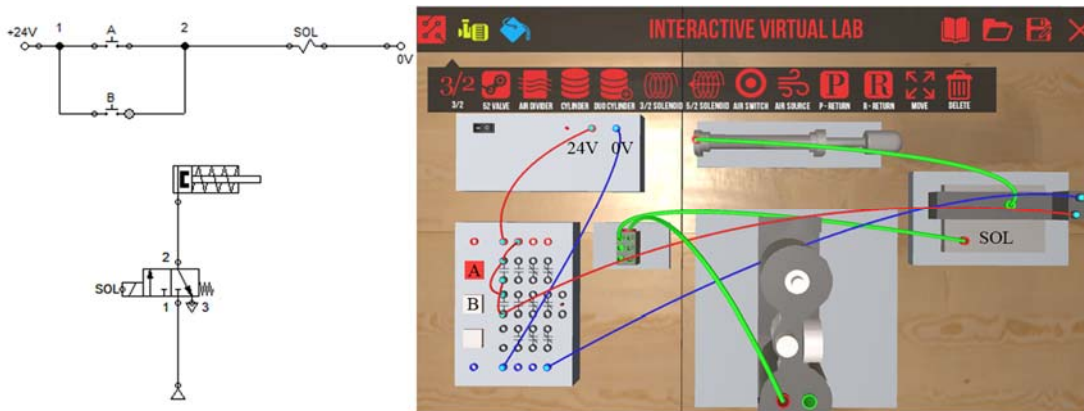


Figure 7. OR Gate Ladder Diagram and Wiring Validation.

Figure 8 shows a NOT gate control logic: when button A is being pressed, there is no air coming out from the 5/2 Solenoid; when button A is not pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

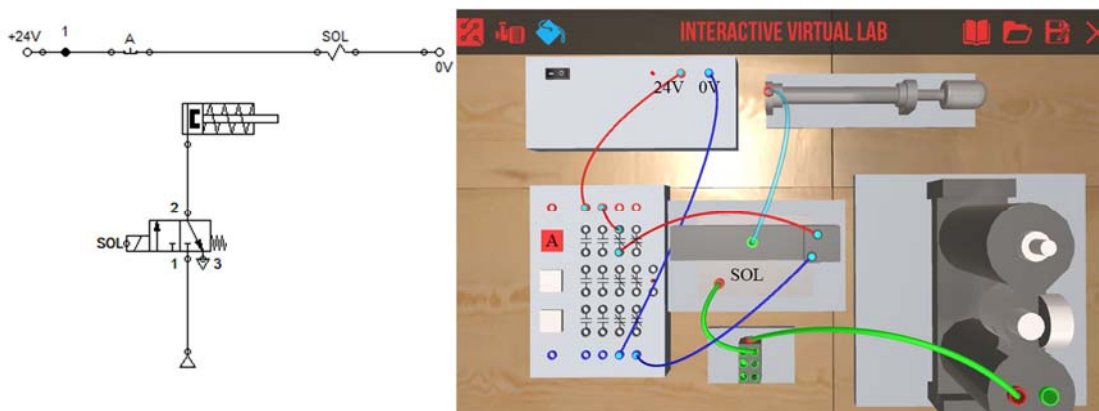


Figure 8. NOT Gate Ladder Diagram and Wiring Validation.

Figure 9 shows a NAND gate control logic: when button A or button B is not being pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

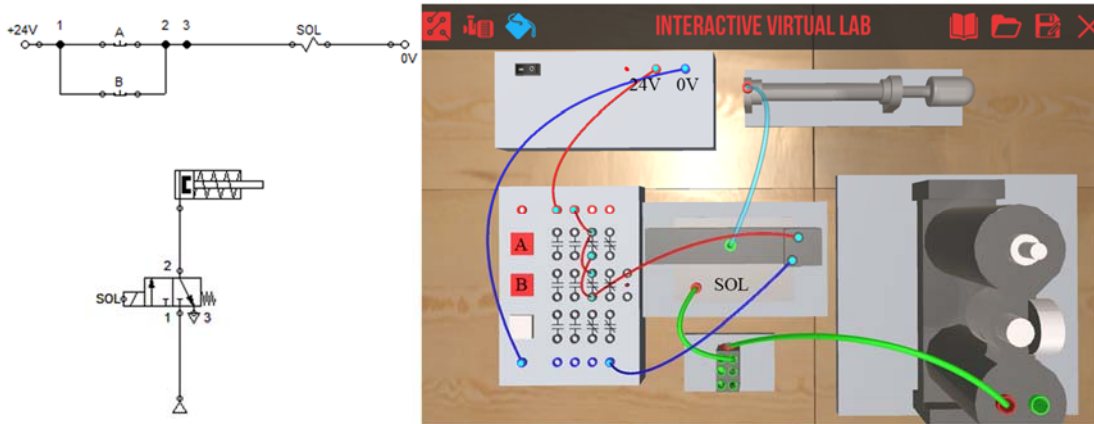


Figure 9. NAND Gate Ladder Diagram and Wiring Validation.

Figure 10 shows a NOR gate control logic: when both button A and button B are not being pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

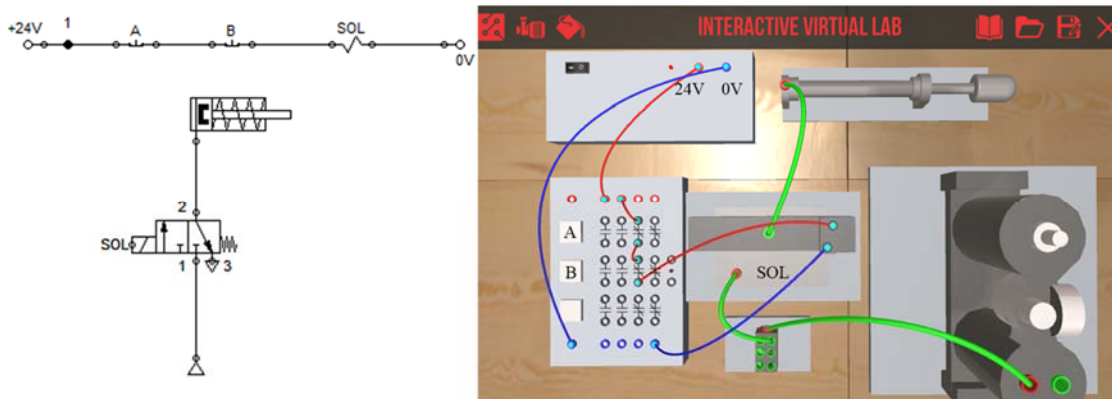


Figure 10. NOR Gate Ladder Diagram and Wiring Validation.

Figure 11 shows electrical relay control logic, when button A is being pressed, the 5/2 Solenoid can transmit the air to the Single Cylinder.

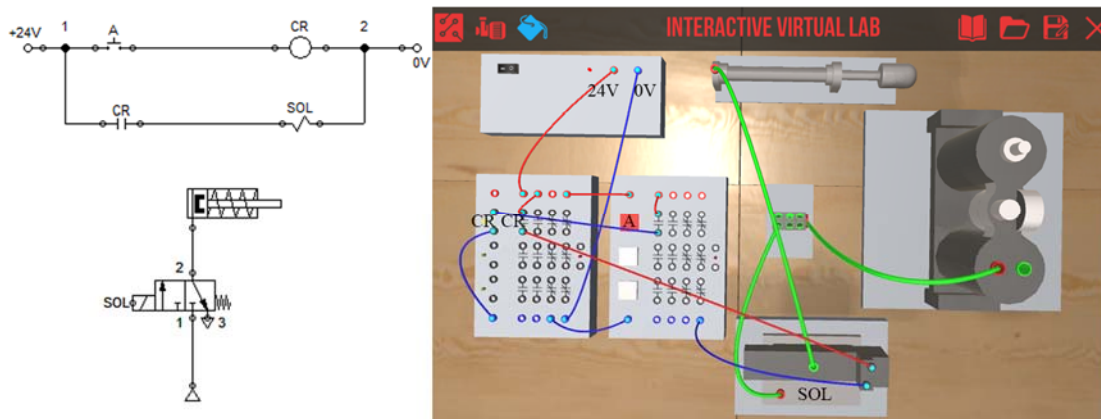


Figure 11. Relay Control Ladder Diagram and Wiring Validation.

Figure 12 shows seal-in control logic: after the first-time button A is pressed, even if button A is released, the 5/2 Solenoid can still transmit the air to the Single Cylinder.

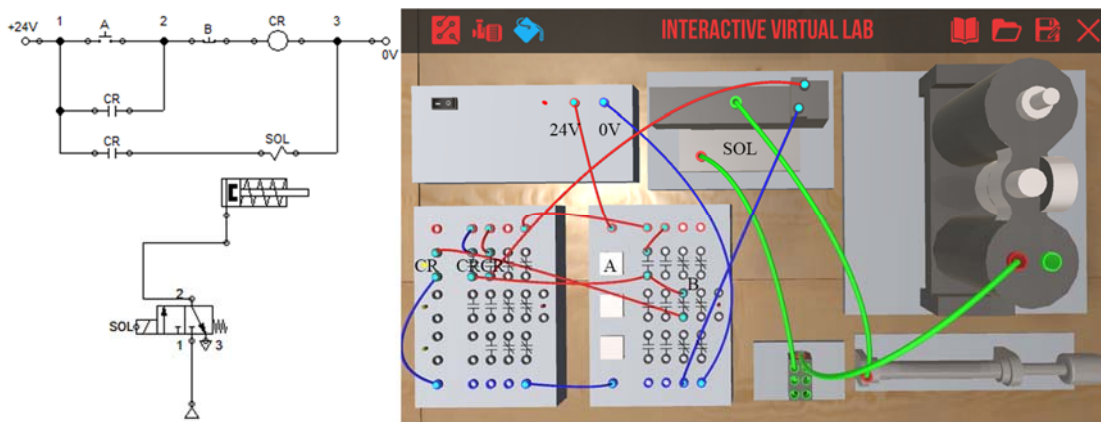


Figure 12. Seal-in Circuit Control Ladder Diagram and Wiring Validation.

A survey was conducted after students used Virtual Lab in the course MET 386 in Fall 2017 semester. The survey contained 5 questions with Likert scale 1-5 as shown in Table 1. Seventeen students returned the survey, which has an average score of 4.19. Only one question (The software is user friendly) received a score lower than 4.0, indicating the user friendliness of Virtual Lab needs further improvement.

Table 1. Survey Questions and Results

5: strongly agree; 4: moderately agree; 3: agree; 2: partially agree; 1: disagree completely	
Survey Questions	Results
1. The software helps me gain the knowledge in electro-pneumatic wiring.	4.41

2. The software functions almost the same as the real equipment.	4.18
3. The software is user friendly.	3.65
4. I would highly recommend the software when no real equipment is available.	4.41
5. The software will be certainly benefit distance learning students.	4.29
Average	4.19

The survey also contained open-ended comments. The following comments were directly from the students.

- 1) "Turn the people's voices off in the back"
- 2) "Works in place of real equipment"
- 3) "Would be nice if it could be available to download for a MAC"
- 4) "Works well but maybe a better selection interface for the parts"
- 5) "Works well"
- 6) "Once devices 'explode' from short circuits, allow them to go away instead of staying on the table"
- 7) "Directions on how to use certain functions"
- 8) "The crashing when you have a short circuit"
- 9) "When deleting elements, the software makes you start over. Very frustrating. It doesn't look the same & took a while to figure out"
- 10) "Could be nice if you did not have to rebuild the circuit when it shorts"

From the survey results, it can be seen students liked the simulation capabilities provided by Virtual Lab, while requesting revision or improvement of certain user interactions. Several comments (6, 8, 10) are related to the short circuit error handling in Virtual Lab, as illustrated in Figure 13. When there is a short circuit error, Virtual Lab displays a visual explosion, turns the power supply to black, and removes all existing wire or air tube connections. This demonstrates an important advantage of Virtual Lab: students can make mistakes in Virtual Lab without causing personal injuries or damage to lab equipment. Different students had dissimilar opinions of how to handle the short circuit error in Virtual Lab. Student One (comment 6) suggested the lab devices such as power supply and switch boxes should be removed when a short circuit occurred; Student Two (comment 8) seems to like the current handling; Student Three wanted to keep the lab devices and wire connections when a short circuit occurred. In this example, Student One and Student Three expressed totally different opinions. Virtual Lab will be further revised to include features that are desired by most students. In addition, a mobile version of Virtual Lab has been developed and runs on Android smartphones and tablets.

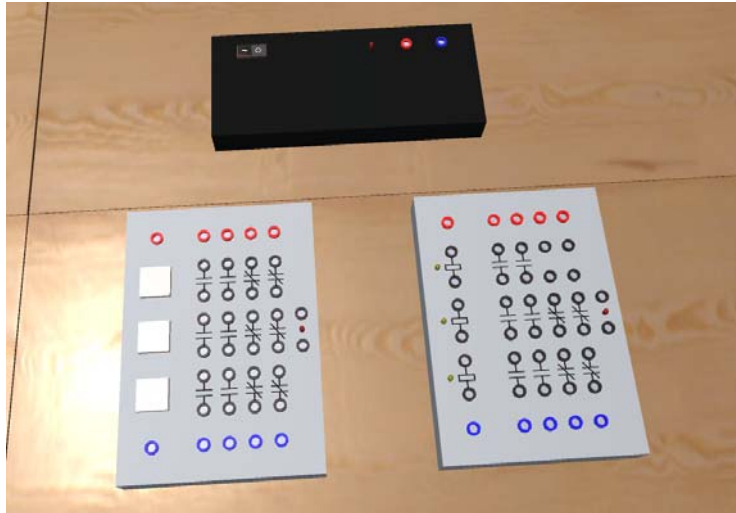


Figure 13. When there is a short-circuit error in the lab configuration, the power supply turns black and the wire (or air tube) connections disappear.

5. Conclusion

This paper described the latest design and development of Virtual Lab, a simulation application for completing programmable control logic (PLC) using mechanical, electrical, and pneumatic components. Virtual Lab now supports a wide array of pneumatic components, such as single-acting cylinder, air divider, 3/2 directional control valve, and 5/2 solenoid control valve. Other new important features of Virtual Lab include direct 3D drag and drop manipulations of lab devices and components, more camera views (e.g., orbit tool), a more user friendly graphical interface, as well as a more realistic rendition of the lab environment. Initial classroom use demonstrated the effectiveness of Virtual Lab. Future development of Virtual Lab will include improvement of user interactions, a web version that will run directly inside web browsers, and expansion to virtual reality devices (e.g., zSpace and Oculus Rift) and augmented reality devices (e.g., Microsoft HoloLens).

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