Hydraulic Trainer for Hands-on and Virtual Labs for Fluid Power Curriculum

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Abstract

Hands-on experiences constitute a high value, perhaps unreplaceable, element of applied engineering disciplines such as fluid power. Hydraulic and pneumatic trainers have been developed over the years to expose students to applications of fluid power technology. However, the traditional approach for educating students through hands-on lab is recently under high pressure due to the following aspects: a) the outdated design of the traditional trainers that seldom integrate modern electro-hydraulic components, data acquisition systems, and visual aids; b) the increased need for online education. These factors have been endangering the number of students – already low compared to the industry needs – enrolled in fluid power programs.

This paper describes the effort made at Purdue University to develop a modern hydraulic trainer along with its digital twin that tackles the above challenges. A novel physical trainer was formulated to allow 29 lab experiences that span from basic concepts of single actuator control to more sophisticated layouts for controlling multiple actuators. The trainer largely uses electro-hydraulic components, sensors as well as a DAQ system connected with a touch base screen, aimed at maximizing the student's feeling of experiencing modern technology. A virtual trainer that replicates the physical trainer is developed and implemented with the commercial software Unity 3D. The virtual trainer uses the CAD drawings of the physical components of the actual trainer, and it allows reproducing all the main aspects of the real lab experience, including typical students' mistakes and realistic operating noise. This trainer simulator was successfully used for the first time at Purdue in Fall 2020, and it will represent a valid option for virtual hands-on experiences for distance learning students for years to come.

Keywords: Fluid Power Education, Hands-on experience, Fluid Power, Virtual Simulator, Online Learning, Object-oriented programming, Digital twin

1 Introduction

Hands-on learning is a significant portion of the learning puzzle for applied engineering disciplines such as fluid power. It does not only make the class material more enjoyable and exciting to students, but it also allows better to engage the students through an active learning process and it helps to fix the basic concepts into each student's mind. Moreover, it can give the feeling of the problem, which cannot be taught, especially for troubleshooting experiences. In fluid power (FP), hydraulic and pneumatic trainers have been successfully used over the last decades for this purpose. A hydraulic trainer is training equipment to support the teaching of hydraulic and pneumatic motion control. It is a customizable test bench with a power unit, valves, actuators, and hoses with connectors. This paper particularly aims at trainers for educating the next generation of engineers in hydraulic control technology. In addition to the development of a virtual learning tool (imitates the real experiments in the virtual world) to support online education. The need for online education was constantly growing until it became an unreplaceable necessity during the COVID19 pandemic.

Many of the existing trainers have relevant limitations with respect to the state-of-the-art applications. From one side, they are often limited with the operating pressure and flow for safety reasons. The flexibility of reproducing both resistive and overrunning loads to the circuit is limited. However, most importantly, the existing trainers usually cover a minimal spectrum of the hydraulic control circuits that are commonly used in fluid power machines. Moreover, the human interface is often too rudimental: as very seldom advanced graphical user interfaces or modern data acquisition and control systems are used to accompany the students towards the accomplishment of a specific experience.

1.1 State of the art

Another significant limitation of most of the existing trainers is on their flexibility. Trainers offered by the fluid power companies such as Amatrol [1], Bosch Rexroth [2], Eaton [3], FPTI [4], Hytech [5], Id System- didactic [6], Parker Hannifin [7], SMC [8], SAP engineers [9], come with specific modules suitable for training only specific concepts. Therefore, it can be challenging, from the point of view of cost and spatial availability, to set up a laboratory where multiple students can simultaneously run experiments in multiple stations. The pre-designed modules of most of the mentioned trainers are often designed for a specific fluid power curriculum, where the different concepts are presented following a pre-determined conceptual sequence. While this can be considered an advantage for the students that can experience well established programs, such design is a great obstacle for instructors that want to experiment with new concepts or follow educational paths different from the pre-designed one.

Many academic institutions (the list here would be very wide, involving most of the academic fluid power labs in the world) use as educational test rigs experimental setups similar to those used for research purposes. A significant example is described in [10]. Such labs constitute in-depth experiences for the students, but they are often unsuitable for providing exposure to basic concepts, circuit assembly, and troubleshoot.

From the considerations above, it is clear the convenience of having available trainers highly flexible, which can be used for training the students with both basic and advanced concepts by using the same working area. Purdue University upgraded a non-commercial version of Parker Hannifin trainers [11] by introducing some advanced experiments related to electrical control and installing a DAQ system, but it is now outdated due to technological advances in the last decade. Festo [12] offers a test bench that allows running basic and advanced labs but lacks a well-designed human-machine interface, which can be a drawback for the students and cannot simulate different loads.

An important aspect of this flexibility pertains to the ability of the trainer to demonstrate different concepts related to the main parts of a hydraulic system: the flow supply (different concepts based on either fixed or variable displacement pumps are available); the control type (pump control, or different type of valve control) different actuators (linear and rotary actuator); different loads (overrunning, resistive). A test station that can reproduce in a compact implementation all the above elements in all possible combinations, even involving multiple functions, can be considered as ideal to educate and stimulate the students to all possible fluid power concepts.
The work presented in this paper not only tackles the above-described challenges but also considers that if such implementation is possible for an actual trainer, then it could be reproduced in a virtual environment in the same fashion for online education.

In the area of online education for hydraulic control systems, there is a wide category of tools that is available to students such as [13], [14], [15], mostly built in academia, in common are limited to few basic experiences without allowing the user to build and assemble the circuit themselves. Moreover, no recent research has been done toward improvements. [16], [17] represent more recent work in that field but still does not give the user the choice of connecting a circuit themself in real-time. The most effective and successful tools easily accessible online for both guided and self-education are those dedicated to the simulation and rendering of hydraulic machines. Here, simulation tools such as FluidSIM [18], Simcenter Amesim [19], Automation Studio [20], Simulation X [21], and hydraulic simulation software by engineering adventures [22] are among the most popular. They allow the users to build a hydraulic circuit of their own and simulate it. However, the mistake that a learner can make with such tools and the related troubleshooting is a typical debugging of a software tool. Using the above tools, the students likely miss a realistic experience of connecting physical components and visualizing the actual operation of the hydraulic system.

With this goal in mind, the authors conceived a physical trainer along with a digital twin that can be used to replicate the lab experiences in a virtual manner. The digital twin utilizes Unity 3D software and the CAD models of the components used in the physical trainer to provide the students with a realistic experience. The process of selecting the components, connecting the component hydraulic ports with hoses, operating the system is reproduced through a graphical interface that also included the audio sounds recorded from the physical trainer. In this way, the instructor can use the virtual trainer in multiple ways to satisfy fluid power curricula of different nature: from online-only virtual lab experiences to mixed virtual and physical labs, to in presence lab where the virtual tool is used in aid of de-densifying the presence of the student at the physical station to respect social distancing rules.

The remaining sections of this paper details mostly the choices made in the design of the physical trainer (section 2). The virtual simulator is briefly presented in section 3.

2 Hydraulic Trainer

The following factors can be considered important for the design of a successful hydraulic trainer that supports a fluid power curriculum via hands-on lab experiences:

a) Spatial requirement. The smaller is the trainer; the higher is the number of trainers that can fit a normal size classroom. This requirement was particularly taken into consideration in this work, considering a design with a flexible working area where the students can easily assemble different hydraulic circuits simply by placing and connecting components from a proper component rack (Figure 1).

b) Cost and safety. In the proposed design, components typical of the mobile market are traditionally less expensive than those used in industrial hydraulics are selected to lower the system cost. The level of power, in terms of maximum flow rate (< 13 l/min) and pressure (<50 bar) chosen for the proposed test stations allows performing all the required lab experiences but limits the typical risks of high-pressure systems and increases the longevity of the selected components. The students are always required to wear safety glasses when working at the trainer and follow the safety instructions provided by the instructor.

c) Human experience. A well-designed test station that uses modern engineering technology increases the appeal of fluid power technology to the students. For the selected design, a touch base screen guides the students to every lab experience, allowing selecting the sensors and the control inputs to the hydraulic components. The IQAN system by Parker will also allow future development for running real-time simulations of the tested systems that can be compared to the actual experiment.

d) Available set of lab experiences. An effective hydraulic trainer can support both basic and advanced lab experiences in such a way that the student can be exposed to the basic concepts of fluid power but also to the state-of-the-art technology present in commercial machines. As will be detailed in subsection 2.1, particular attention was put on formulating a design of the test station with respect to the experiences available to the instructor.

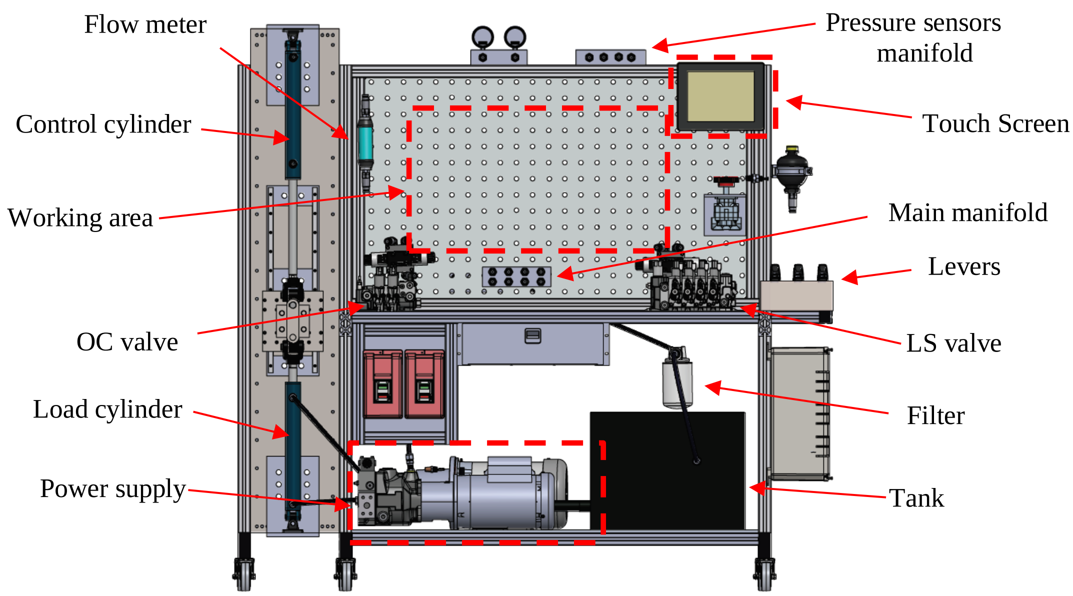


Figure 1:Trainer stand CAD drawing.

The last two points, c) and d), are not trivial for fluid power technology. As stated during SICFP95 by Rob Koski, “With a few notable exceptions, engineering colleges and universities worldwide have generally ignored fluid power as a subject.” [23]. This statement still holds in 2021, with negative consequences to: (i) the number of engineering students introduced to fluid power and (ii) the lack of established textbooks and educational curriculum available to the students interested in learning this technology. This means that, still today, there is not a commonly accepted education method in fluid power available in academia. This latter statement is also consistent with the lack of textbooks that covers the basics as well as most important aspects of the modern fluid power technology. Several textbooks, such as [24], [25], largely focus on the architecture and the operating features of important fluid power components, but lack in providing a system level approach for designing fluid power systems. Other textbooks, such as [26], [27], privilege the analysis of servo-hydraulic systems and do not cover the technology commonly used in off-road machinery. Milestones textbooks such as [28], [29], and [30] focus a lot on the basic theory behind the functioning of hydraulic control systems, but they are not up to date with the modern technology. Finally, other books, such as [31], [32], are suitable only to specific aspects of fluid power technology, such as positive displacement machines and hydrostatic transmissions. All the above textbooks are successfully used at different colleges, as an indication that an established method for teaching fluid power still does not exist. Therefore, it is intuitive how the situation as pertains to hands-on experience is even more sparse, and very often, trainers used in academia are conceived by the fluid power industry, as it appears in the references provided in the previous section.

The above premise is provided to stress the fact that the selection of a proper set of lab experiences to educate hydraulic engineers is far from being obvious. In the trainer presented in this work, the effort was put in providing a useful set of experiences that can be used to support fluid power programs that conceptualize a fluid power from the point of view of the supply type (impressed flow / impressed pressure), and actuator control type (primary control, metering control, secondary control). Therefore, the basilar elements are provided with a simple hydraulic system involving no actuations (for the demonstration of key component features) or single actuation. More advanced hydraulic circuits, such as systems with multiple actuators, are then provided as an extension of the basic circuits. This philosophy of educating engineers in fluid power is a recent trend consolidated in some recent textbooks, such as [33], [34].

2.1 Lab experiences

Hydraulic control systems offer multiple possible layout architectures to control hydraulic functions. These architectures often present substantial differences regarding the control features and hydraulic components used in the system. Hydraulic systems used to control a single actuator can be classified according to two criteria. The first criterion is the supply concept. In a hydraulic system, the supply is the pump, which can operate as a flow supply or pressure supply. Pressure supply is when the pump is adjusting its displacement to keep a given pressure. The second criterion is the control concept. Based on the control element location in the circuit, the system architecture can implement different control methods: primary control, metering control, and secondary control. Figure 2 combines in one figure all the possible configurations. By combining all possible control concepts with all possible supply concepts, 12 methods for controlling an actuator can be realized (most of these with proper variants, as discussed in [34]). Every single circuit has its own features, uses different types of components, and behaves differently according to the nature of the load (i.e., resistive vs. overrunning). The great majority of today's hydraulic systems are based on the metering control, where the control element is located in a valve between the supply and the actuator, where actuators can be placed in series or in parallel with respect to the flow supply.

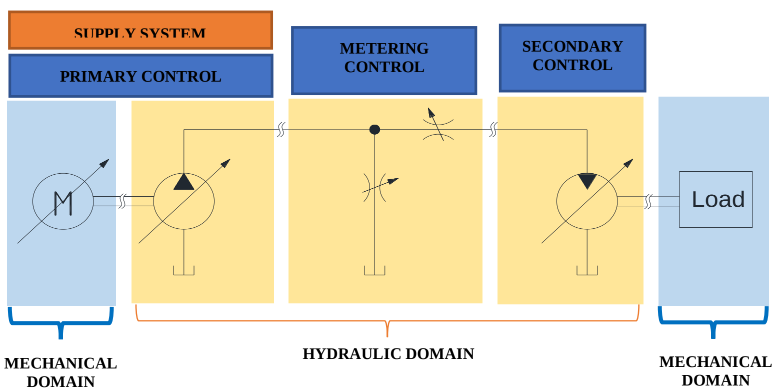


Figure 2:The basic control concepts involved in the control of a single actuator.

Following the above strategy of illustrating hydraulic control concepts, the proposed trainer offers multiple labs for both single-user and multiple-user architectures and also allows establishing different levels of load, including resistive and overrunning conditions. In addition to these labs on hydraulic control concepts, the trainer allows some component-focused or troubleshooting-related labs as detailed in Table 1 and Table 2.

The component-focused experiences are suitable to demonstrate the basic features of the lab (such as setting the maximum operating pressure while studying the behavior of the main pressure relief valve) as well as to demonstrate the basic functioning of some key components used in a hydraulic system. Of particular relevance is the pump characterization lab experience, where the flow vs. pressure performance of the main pump installed in the trainer is tested for the students.

The troubleshooting experiences are designed to expose the students to some practical troubleshooting concepts typical of real systems. Of relevance is the aeration and cavitation test, where one of the pumps installed in the rig is forced to operate in a condition of low suction pressure with the possibility of introducing entrained air into the system (see the schematic of Figure 3). Another test suitable to develop the student's ability to use the theoretical concepts of hydraulics for troubleshooting purposes is the cylinder leak test (Figure 4), where it can be determined if the cylinder seal has internal leakages by observing the piston motion during the tests.

The single actuator tests are listed in Table 3. The table shows the tests used at Purdue to educate undergraduate students, but the flexibility of the trainer would allow for a much longer list. The majority of the circuits aim at demonstrating the metering control technology, which has a lot of variants and market applications. A test is designed for primary control systems. Secondary control is currently not implemented on the trainer, but it will be an easy extension that will be implemented in the future. The tests designed for the single actuator control permit to illustrate and tests the basic features of metering control. For this purpose, basic circuits with meter-in and meter-out orifices (needle valves) are tested on an actuator at which the load (either resistive or overrunning) can be set by the student. After these basic experiences, the trainer allows studying architectures typical of the current state of the art, based on open center circuits, load sensing circuits, or additional components such as counterbalance valves. An experience is also designed to test the capability of an accumulator to recover energy. The most significant schematics are reported in brevity in Figure 5. Each one of these experiences permits the student to build and operate the system, and most importantly, to acquire the most important data necessary to validate the theoretical equations that govern the system. These sensors are shown in the schematic of Figure 5. In many cases, the lab instructor purposely omits the location of the sensors so that this can be added as one of the learning objectives of each experience. The students must build each circuit of the experience by connecting the relevant hydraulic components with quick connectors.

Table 1: List of hydraulics troubleshooting labs experience.

Hydraulics Troubleshooting		
T1. Aeration, Cavitation, and Entrained Air	T2. Cylinder Leak Test	T3. Cylinder Cushion

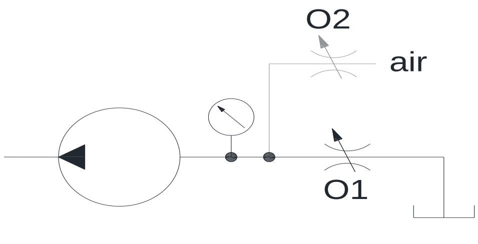


Figure 3:Aeration and Cavitation lab schematic.

Table 2: List of component characterization labs.

Component Characterization			
C1. Pump Characterization	C2. Valve Characterization	C3. Maximum Relief Pressure	C4. Proportional Hydraulics

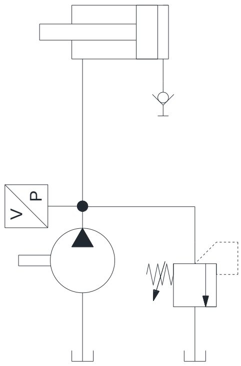
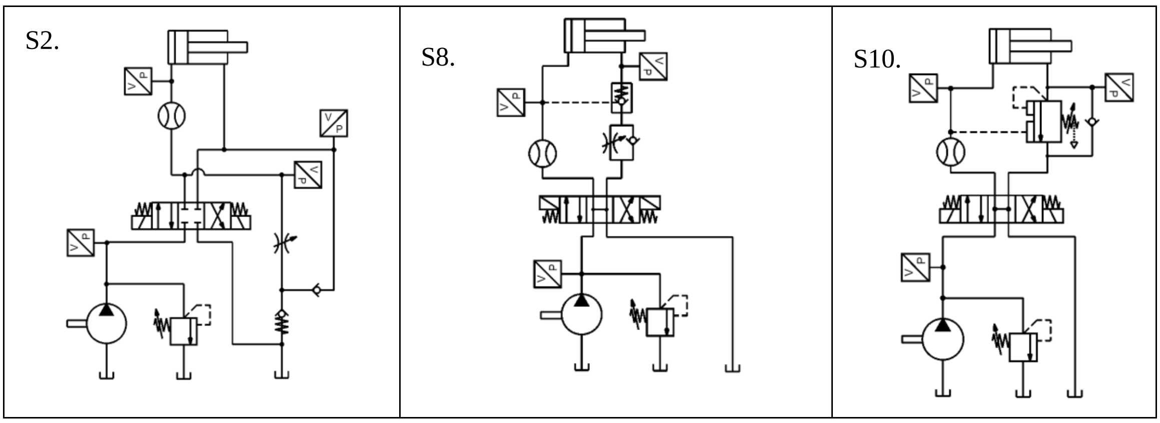


Figure 4: Cylinder leak test schematic.

Table 3:List of single user lab experiences.

Single Actuator Labs	
S1. Maximum Bleed-off	S2. Unloaded Pump Condition
S3. Pump flow rate through an orifice	S4. Sequence Circuit
S5. Basic Circuit	S6. Open Center Hydrostatic transmission
S7. Regeneration	S8. Passive Load Holding
S9. Meter-in	S10. Counterbalance Valve
S11. Meter-out	S12. Constant Pressure System
S13. Unloading Circuit	S14. Load Sensing System
S15. E-LS system	S16. Load Sensing System with a Fixed Displacement Pump



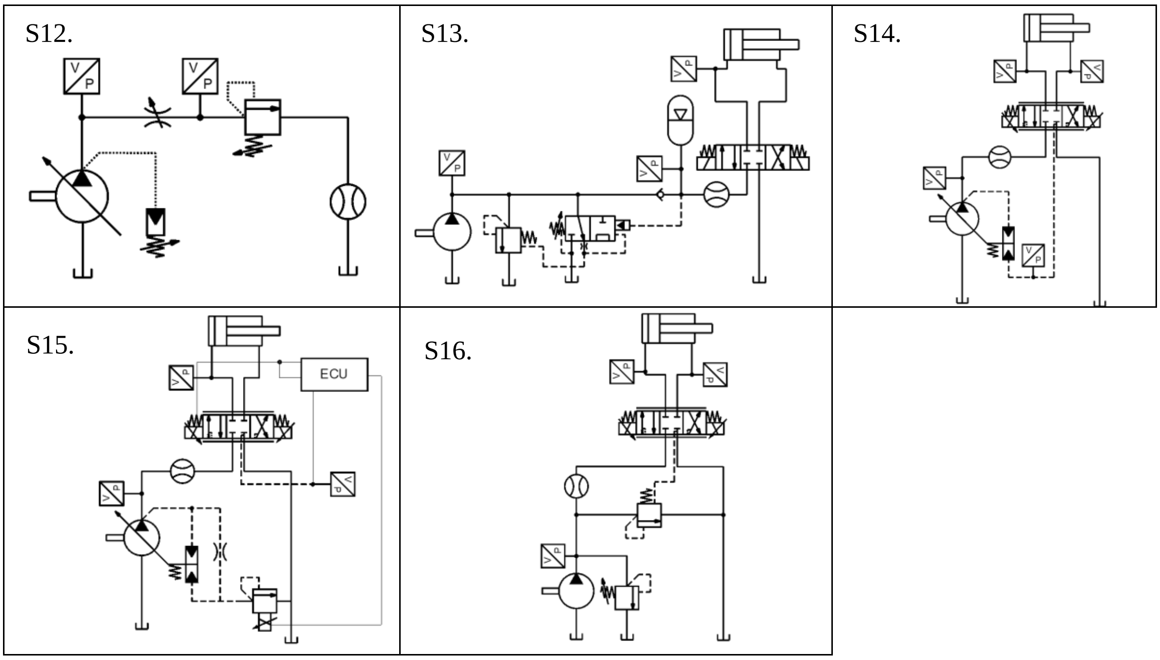


Figure 5:Simplified circuit layout of single actuators

The single actuator experiences build the basis for progressing towards the study of multi-actuator circuits. Multi-actuator circuits reflect the typical design of common fluid power machines. In multi-actuator circuits, a single flow supply – prime mover is used to drive multiple functions. Depending on the circuit layout, series or parallel, aspects of pressure summation or flow summation occur at the supply line. These aspects can be easily illustrated by using two actuators. Two actuator circuits are also used to analyze the aspect of load interference between different actuators present in the same circuit. This pressure interference causes different behaviors with respect to the synchronization between the actuator motion. These aspects of control are shown with the circuits that are summarized in Table 4. The ISO schematics for these labs are shown in Figure 6. Lab 1 represents a circuit with a cylinder and motor with two independent pressure levels, and it is suitable to demonstrate the above concepts when a pressure reducing valve is used to control one of the circuits. Lab 2 shows the aspect of synchronization and pressure amplification in the case of series configuration. Lab 3 focuses on an open center system with two cylinders and illustrates the typical load interference aspects of these circuits. Labs 5 and 6 are dedicated to the load sensing control technology that is very often used in mobile machinery. The aspects caused by different choices on the valve compensator design are shown in two separate labs. Similarly, to the single actuator experiences, also, in this case, the students, by selecting the location of the sensors, can plot pressure vs. actuator flow information to analyze the aspect of controllability and energy efficiency of each system.

Table 4: List of multiple user lab experiences.

Multiple User Mobile Hydraulics		
Fixed displacement System	**Constant Pressure System**	**Load Sensing System**
M1. Dual Pressure Circuit M2. Multiple User in Series M3. Multiple User Open Center System	M4. Multiple User Constant Pressure System	M5. Non-Compensated LS System M6. Pre-Compensated LS System

Overall, the authors selected 29 labs as effective to provide undergraduate students an optimal complement to the theoretical lectures of a traditional fluid power class (3 credits, 36 hrs). However, the flexibility of the trainer allows performing additional tests to accommodate a different selection of labs or a higher number of labs (such as in fluid power programs formed by multiple classes). 29 experience might hardly be feasible in a single class. Nevertheless, the number can accommodate different instructor preferences. Most importantly, having many experiences can open the instructor to change the traditional homework assignments from worked problems to more insightful lab experiences that the student can run in replacement to the homework.

The control valves that allow performing all these experiences can be classified into three different categories: the directional control valves, pressure control valve, and flow control valves. These components are tabulated in Table 5, Table 6, and Table 7, respectively.

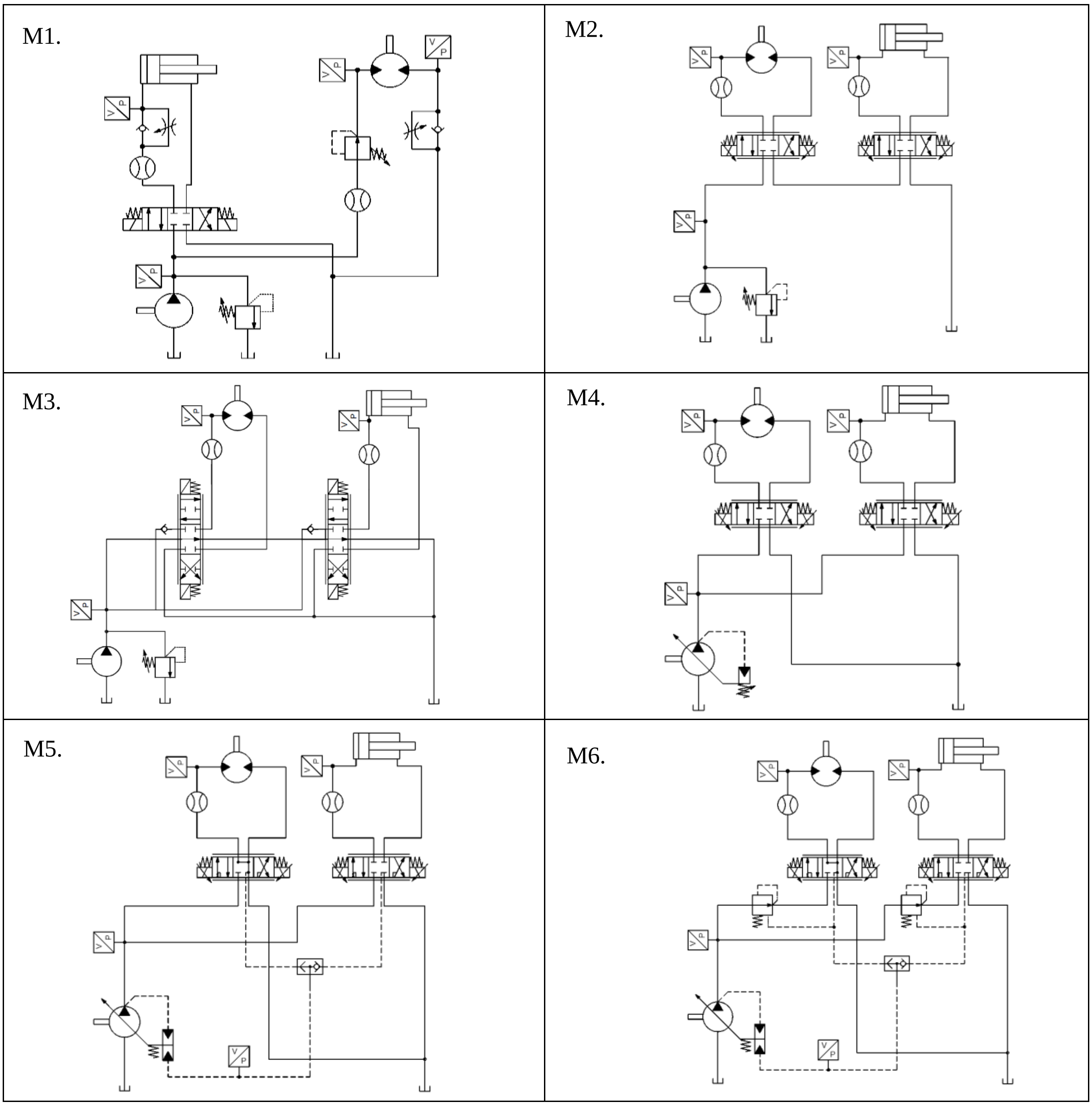


Figure 6: Simplified circuit layout of multiple actuators.

Table 5: Directional Control valve product number.

DCV	Product Number
LS valve	Parker L90LS
OP valve	Parker P70CF
Directional valve	ParkerD1FB
Directional valve	Parker D1VW
Check valve	Parker PSK20610
Loaded check valve	Parker CVH081

The LS valve and the Open Center (OP) valve are customized to meet the low flow requirements of the trainer (10.5 L/min). The LS valve consists of four sections. The first two are non-compensated valves, one is a motor

spool, and the other has a cylinder spool. The other two are pre-compensated valves with a compensator setting of 5 bar, similarly, having a motor and cylinder spool. This valve can be controlled either manually with the mechanical levers or electronically through the DAQ. The OP valve has two sections solenoid operated.
Three directional valves (4-way 3 position), two of them are proportional closed center valves. The other is an ON/OFF open center valve.

Table 6:Pressure Control valve product number.

Pressure control valve	Product Number
Pressure reducing valve	Parker PSK20614
Pressure relief valve	Parker RD102K09
Counterbalance valve	Parker E2B02
Unloading valve	Parker RU104
Logic element	Parker 10SLC2-A-75
Logic element	Parker 10SLC2-A-25

Table 7: Flow control valve list.

Flow control valve	Product Number
Needle valve	Parker PSK20608
Pressure compensated Flow control valve	Parker PSK20611
Flow control valve	Parker PSK20609

2.2 Power Supply

Many considerations were put on the choice of the supply pump to be used in the trainer. The main goal was to achieve a supply that can be suitable to operate as both fixed and variable flow supply. For the case of variable flow supply, the desire was to allow the unit to operate with both pressure compensating mode, as in a constant pressure system, or flow compensating mode, as in a load sensing (LS) system. The choice was to modify the basic layout of a 16 cc/rev LS axial piston pump, as shown in Figure 8. The power supply has three ports connected to the main manifold, as shown in Figure 1, with quick disconnectors on the user's side. Next to the pump, Figure 7 shows the flow compensator of the pump, which reduces the pump displacement to set an outlet pressure equal to the pressure value at the LS port pressure plus a margin. The LS signal is connected downstream of a needle valve placed between the pump outlet and port 1 of the manifold. In this way, the pressure drop across the needle valve is always equal to the pump margin. In this way, setting the needle valve opening allows controlling the pump flow provided to the system.

$$Q = C_f \Omega_o \sqrt{\frac{2(p_p - p_{LS})}{\rho}} = C_f \Omega_o \sqrt{\frac{2s}{\rho}} \tag{1}$$

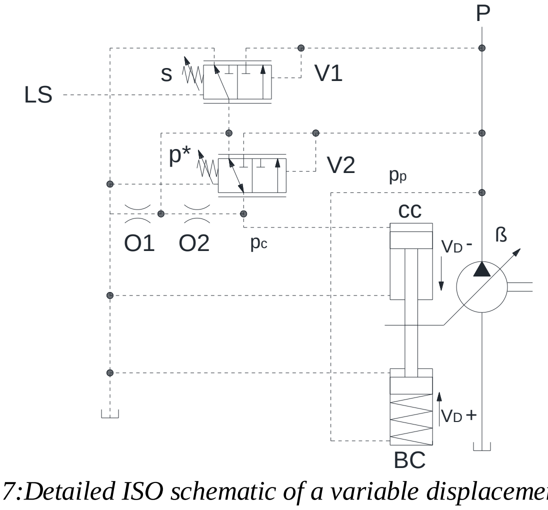


Figure 7:Detailed ISO schematic of a variable displacement pump.

This operating mode allows setting the flow rate of the pump and allows the students to "see" the flow supply as a fixed displacement pump. In this scenario, the IQAN system displays on the screen the pump volumetric efficiency as a function of the system pressure in real-time. If the user connects port 2 as an outlet and port 3 to the LS line, the pump then behaves as a traditional LS unit where the needle valve and the bidirectional ON/OFF valve are kept fully closed to avoid any interference with the LS signal. Connecting to port 2 and choosing with the DAQ to operate as a constant pressure system, that activates the bidirectional valve allowing the pressure reducing valve to control the LS signal and therefore the pump outlet pressure independently from the load information and only based on the user command to the reducing valve. In a similar fashion, an Electronic-Load Sensing flow supply is achieved by letting the user to identify which pressure sensor is transmitting the pressure information to the pressure reducing valve. Figure 9 summarized all the operating modes of the flow supply.

The pump pressure range is between 17-69 bar, but for safety reasons, the maximum pressure is set at 50 bar by adjusting the pressure limiter setting. The pump displacement is 16 cc/rev, but its maximum swashplate angle was limited to provide a maximum flow rate of 10.3 L/min at a speed of 1800 rpm of the prime mover.

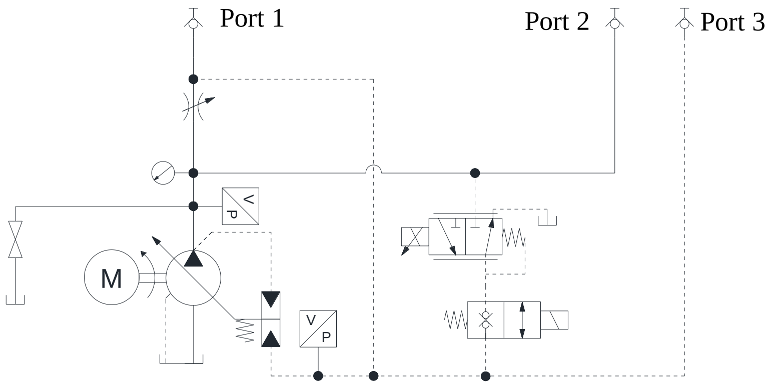


Figure 8:Trainer power supply ISO schematic.

Table 8: Power supply hardware.

Power Unit	Product Number
Axial Piston Pump	Parker PVP16102A
Pressure control valve	Parker EPR111C
Needle valve	ParkerD1FB
Bi-Directional valve	Parker GS02700NS
Shut-off valve	Parker V500CS6

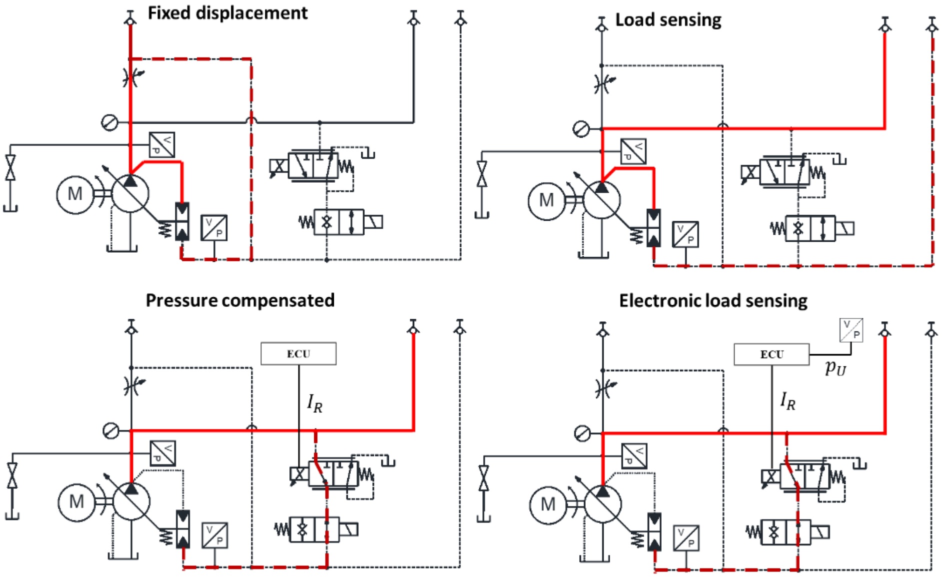


Figure 9:Different power modes of operation of the supply unit functions.

2.3 Actuator and Load module

An original feature of the presented hydraulic trainer is the capability of testing different circuits for various loads acting on the hydraulic actuators (resistive or overrunning). This is achieved by a dedicated load module which can be represented with the schematic of Figure 10. The cylinder used in the test circuit is referred to as "control cylinder": this cylinder will be connected by the student with either one of the circuits discussed in the previous section 2.1 by using quick connectors. This control cylinder is connected to a "load cylinder," which is connected to an auxiliary load circuit, whose components are listed in Table 9. The load cylinder is used to set the desired force acting on the control cylinder, in both directions. This is accomplished by two reducing/relieving pressure valves used to control the pressure in the cylinder chambers and, consequently, the load force. Cylinders are coupled with dual-axis aluminum roller guides to compensate for any possible side forces due to unavoidable misalignment. Users can set the load force using the DAQ. The force range varies between 0 and 3.5 KN in the case of resistive and 0 to -500 N in case of overrunning. Using two pumps allows to control each chamber pressure separately and permits the use of a smaller electrical motor.

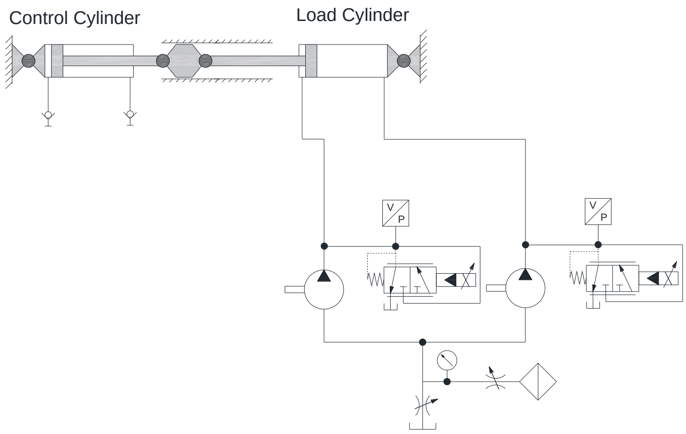


Figure 10: Load module structure.

The auxiliary circuit that supplies the load cylinder is based on a tandem gear pump. Due to the high capabilities of gear pump to handle cavitating conditions, the same unit is used in combination with a variable orifice that was installed with a tee connection having a pressure gauge and a needle valve for aeration to allow the lab experience T1 (Table 1) previously mentioned.

Table 9: Components used in the load module circuit.

Component	Product number
Tandem Gear pump	Parker PGP505
Hydraulic cylinders	Parker 1.50BBRDH
Pressure control valve	Parker EPR111C
Hydraulic cylinder	Parker PSK20603
Bidirectional motor	Parker PSK20618
Needle valve	Parker N400SS
Industrial ball valve	Parker V502SS-8
Muffler	Parker EM25
Pressure gauge	Wika 0 to -30 IN HG

2.4 Trainer GUI, DAQ, and Sensors

Parker Hannifin's IQAN electro-hydraulic control system was installed on the trainer to be used as an intelligent DAQ (master control). The master control offers an interactive and intuitive human machine interface. The master control includes a 24 V DC power supply, an MD4 10.1" touch display, XC43 expansion module, levers, pressure sensors, flow meters, position sensor, and a speed sensor. Figure 11 schematically shows the instrumentation for the trainer, along with the approximated location of each sensor and valve. All the selected parts are listed in Table 10.

The Parker IQAN-MD4 serves as a touch display, interface, and controller. The XC43 expansion module allows up to 50 sensors of voltage, current, digital, and timer inputs. It permits the control of 36 valves with different outputs, either proportional or digital. The module communicates with the touch display over a CAN bus. The master control allows exposing the students to the basic features of electronic control, sensors, wiring schematics, calibration, diagnostics. The authors believe that this use of HMI, based on GUI, DAQ, and the use of electronic sensors instead of traditional gauges, contributes to stimulate the students about the learning of engineering aspects outside traditional hydraulic control systems, and at the same time provide a modern perception of the trainer.

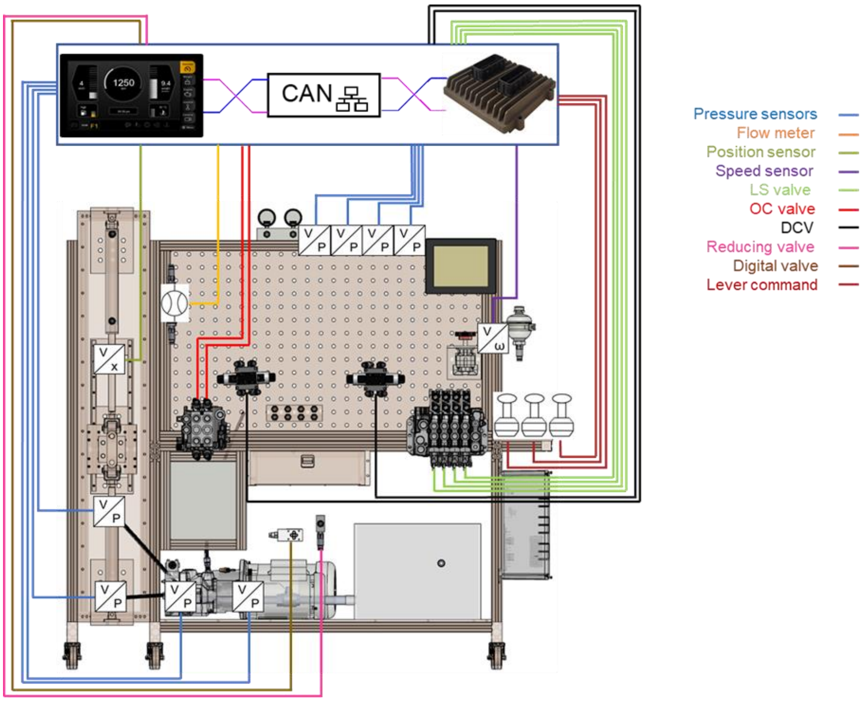


Figure 11:Master control diagram for reference trainer.

The code development and testing are done through the IQANdesign [35], which is a graphical design tool. The system allows recording the data into an excel file to facilitate an offline data analysis.

A user-friendly GUI was formulated and implemented. This GUI has a top-down structure that allows the student to navigate between the pages using the touch screen. It starts from choosing different kinds of power supply, reading the sensor's value while running the experiment, changing the units between metric and imperial if needed. The GUI provides the chosen labs list, allowing the student to visualize the hydraulic circuit to be connected, the description of the lab's experience, and the instructor questions they need to answer. This also eliminates the need for a printed handout. The user can also install Simulink models for online model validation. Another available feature is implementing and testing Simulink controllers with any hydraulic circuit opening the opportunity to teach advanced control classes. A GUI example related to the multiple user open center lab is shown in Figure 12. The GUI also allows asking multiple-choice questions at the trainer stand.

Table 10: List of master control components.

Master Control hardware	Product Number	Output type
Power Supply	120 V AC/ 24 V DC	/
Expansion module	Parker IQAN-XC43	CAN bus
Touch screen	Parker IQAN-MD4	/
Pressure sensor	Parker IQAN-SP	Voltage 0.5-4.5V
Flow meter	Parker SEN40601	CANopen
Position sensor	ASM WS31C	Voltage 0.5-10V
Speed sensor	Parker 01712ECD	Frequency
Lever	Parker IQAN-LST	Voltage 0.5-4.5V
Pressure gauge	Parker PSK20615	Visual
Flow meter	Parker PSK20612	Visual

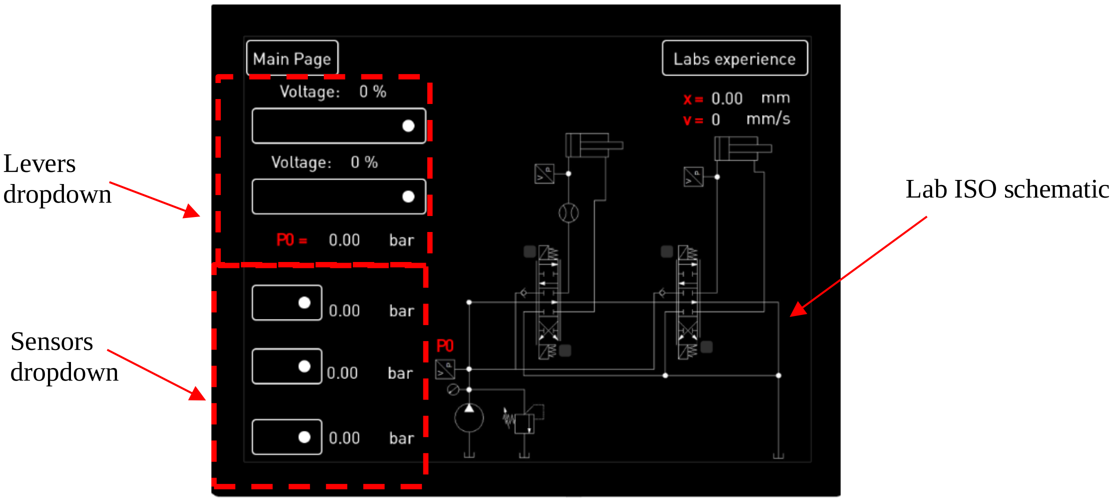


Figure 12:GUI lab experience example.

2.5 Actual Implementation

The trainer stand's design was done starting from the CAD drawing of the current Parker Hannifin trainer [7] and modified to be suitable for the new setup shown previously in Figure 1. It is a double-sided learning platform. One side is used for hydraulics, while the other is used for the pneumatic module. The frame is made with aluminum, and dimensions are 1.72 m high* 1.72 m wide* 1 m deep. The trainer stand has two power units with the corresponding motor starters, a hydraulic tank with a capacity of 75 liters, where a filter is installed at the return line. DAQ, electronically controlled valves, and the load module fixed to the frame. The electronically controlled valves are fixed and secured, so students do not need to change or connect the electrical wires while building the circuit.

The development of the proposed trainer occurred with an initial prototype, developed at the authors' Maha Fluid Power Research Center, followed by a final implementation installed at the Purdue Agricultural and Biological Engineering fluid power motion control lab sponsored by Parker Hannifin (Figure 13). Parker Hannifin also provided support and components for the implementation of the trainers. The prototype of the trainer was essential to test the supply circuit, the load module, the controls, and every single lab experience.

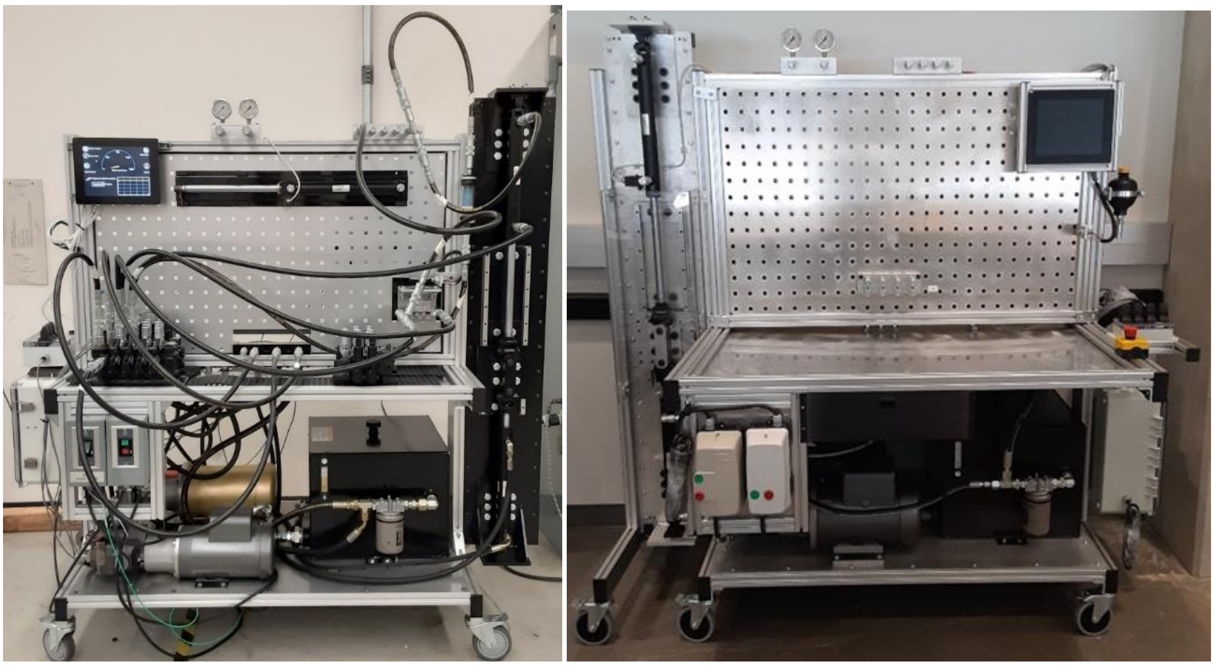


Figure 13:Actual hydraulic trainer: prototype (left); final implementation (right).

Figure 14 shows the components carrier that is double-sided, so every two trainers will need one of them—also having the hose racks as highlighted in the figure.

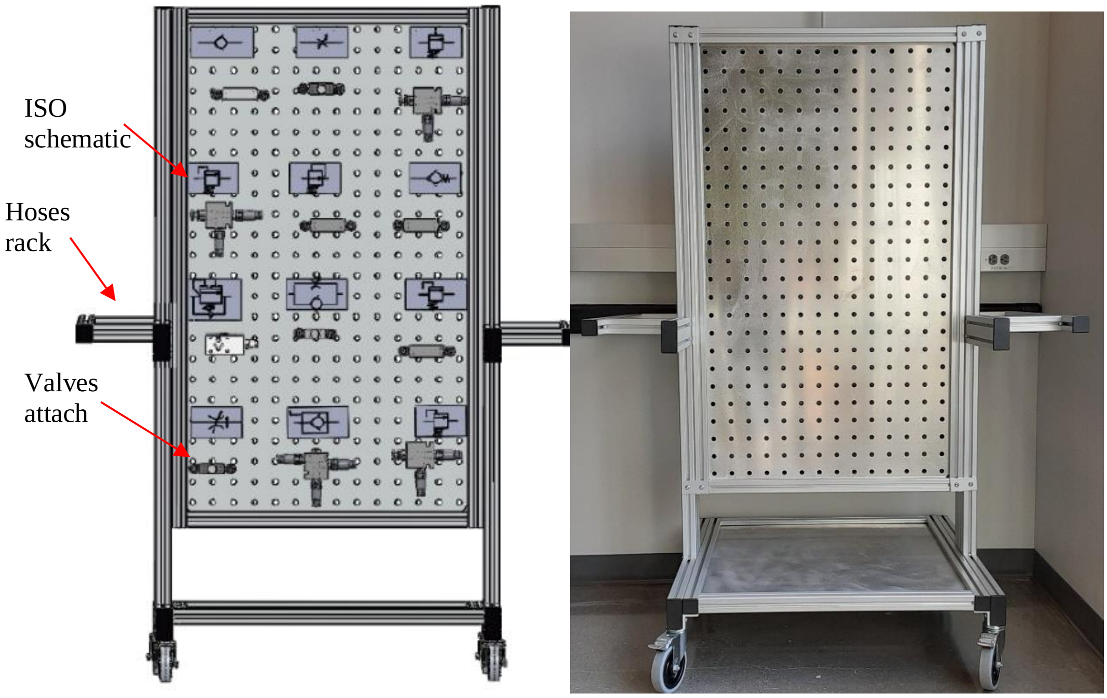


Figure 14: Component carrier CAD (left); final implementation (right).

The component carrier's spirit comes from the simulation tools, in which the user drags the valve from the library into the working area to build the circuit. Here the idea is similar the valves are attached to the component carrier while they are not in use. The user picks up the valve after looking at the ISO schematics and attaching it to the trainer stand. That will make the digital twin look realistic.

3 Virtual Simulator

As mentioned in the introductory section of the paper, the development of a digital twin of the trainer implemented in this work constitutes an essential part of this project. The modular implementation of the trainer, with a drag/drop approach for placing hydraulic components to be connected with quick couplers, was replicated in a software environment to allow the students to perform the same lab experiences using a digital platform (computer, tablet, smartphone). The simulator can be entirely operated from the web or through an App that can be installed. No additional help is needed from the instructor. Like in an actual lab with the physical trainers, the student needs to build and operate the circuit just by looking at the lab handout, inclusive of the hydraulic schematic and lab goals. Unity3D is used as the virtual simulation environment. The software is a typical game engine development tool, which permits creating a real-time 3D project in discipline fields. In the simulator, the user can drag the components rendered with actual CAD drawings from the component carrier to the trainer stand and connect them using the hoses with quick disconnectors. The tool is easy to use, especially for those who worked with the actual trainer before. Unlike the physical trainer, this does not have any safety concerns. Indeed, the virtual trainer also allows overcoming the pressure and flow limitation of the physical trainers for the execution of certain labs (such as the pump characterization, where it is desirable to exceed the 50 bar pressure limitation). The actual CAD of all components was imported from SolidWorks into Blender as STL files. Inside Unity, a universal render pipeline used for graphics optimization was implemented to improve the appearance further. After the visual part, each component was modeled with it is own equations using an object-oriented programming C#. Further details on the implementation choices of the software will be provided in future publications.

A crucial aspect of the virtual trainer is the possibility of reproducing some of the mistakes that an actual student can make in the physical trainer. This usually consists of allowing an incorrect sequence for connecting the components. The virtual trainer also uses sound clips taken from the actual trainer when components are connected or when the system is operated.

A GUI was built to reflect the master control present in the physical trainer. It is possible to switch two modes using a toggle, building, and running mode. The building mode is meant to build the hydraulic circuit where it is possible to see the component carrier with the valves and hoses, while in the running mode, these features disappear, and the master control will show up. Electrohydraulic proportional valves are also controlled differently from manual ones: the first is controlled using an electronic lever, and the last using a mechanical lever.

As an example, Figure 15 shows lab S9 from Table 3, where an orifice with a bypass check valve is used to control the motor speed. The master control is showing the hydraulic schematic along with the sensors and levers. The lever is used to control the DCV, and a slider manages the opening area of the orifice based on the user's command. While in the right, the trainer stand is shown with the circuit connected.

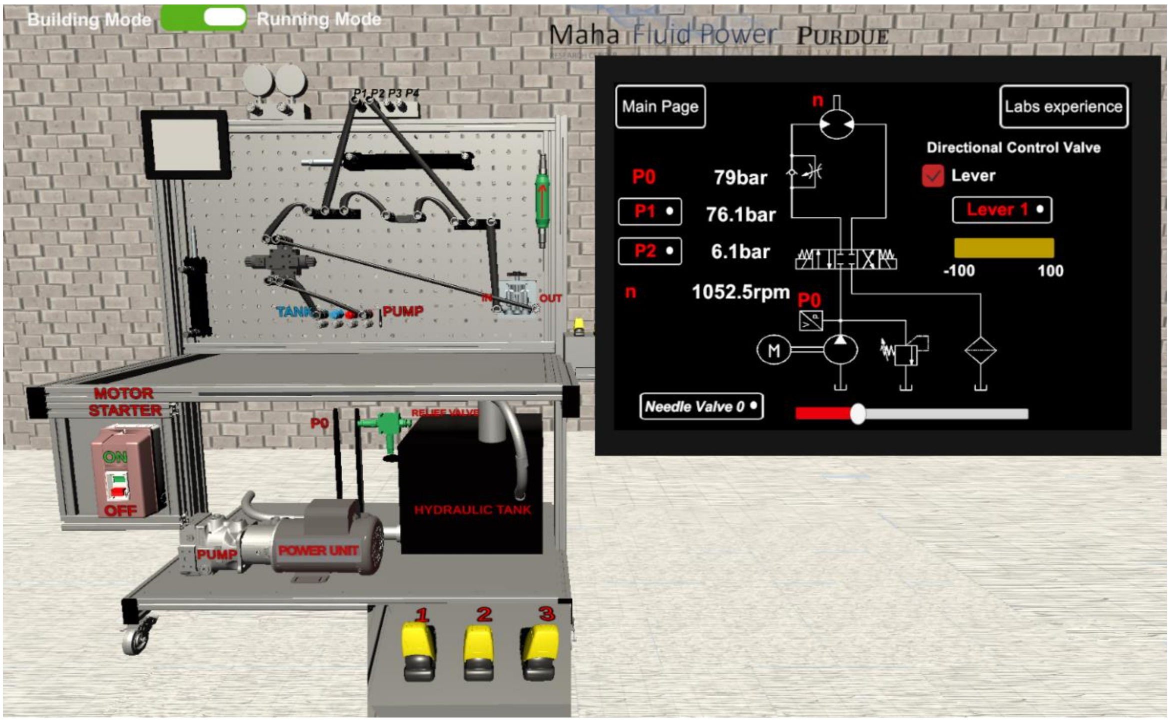


Figure 15: Virtual Simulator lab experiment setup.

4 Conclusion

This work focused on a new hydraulic trainer that was developed at Purdue to support education in fluid power classes. The trainer fulfills the needs of having a flexible structure where the hydraulic circuits can be built in a drag/drop fashion. The use of modern DAQ, such as touch screen and sensors make the trainer appealing to students. The choice of the lab experiences allowable by the trainer suits classes where hydraulic control technology is taught with respect to the basilar concepts of primary control, metering control, and secondary control. Each system is presented considering different options of flow supply (fixed or variable flow supply) or of load acting on the actuator (resistive or overrunning). A total of 29 experiences are referred to in this paper, even if a larger number is easily allowable. The trainer was successfully developed during 2020 and implemented in its final version in early 2021. It is currently successfully adopted in fluid power classes at Purdue University. To fulfill the recent needs for online education, a virtual trainer was developed in Unity 3D to replicate the physical trainer. The virtual trainer allows executing the same experiences in a realistic fashion, using a visual rendering based on 3D drawings of the actual components and sound clips recorded from the physical trainers. The virtual tool was used for the first time in Fall 2020 in a fluid power class involving 18 senior undergraduate students. The trainers and their digital twin were the main practical experience offered in the class. Under the class questionnaire "The projects or laboratories aid me in achieving the class objectives" 75% of responses were "strongly agree, and 16.67% agree".

Future work will involve adding more lab experiences, especially on hydrostatic transmissions taking advantage of the modularity of the setup.

Nomenclature

Designation	Denotation	Unit
Q	Flow rate	L/min
p_p	Pump Pressure	bar
p_C	Cylinder pressure	bar
p_M	Motor pressure	bar
Q_p	Pump flow rate	L/min
Q_c	Cylinder flow rate	L/min
Q_M	Motor flow rate	L/min
s	Pump margin	bar
T	Troubleshooting	
C	Component	
S	Single User	
M	Multiple User	
FP	Fluid power	
LS	Load sensing	
DCV	Directional control valve	
HMI	Human machine interface	
CBV	Counterbalance valve	
E-LS	Electronic load sensing system	
OP	Open center	
V1	Differential pressure	
V2	Absolute pressure limiter	
CC	Control cylinder	
BC	Bias cylinder	
β	Swashplate angle	radian
p_c	Control pressure	bar
p_p	Pump pressure	bar
O1, O2	Dynamic office	
V_D	Pump displacement	cc/rev
p^*	Pressure setting	bar
GUI	Graphical user interface	
IQANdesign	Graphical design tool	

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