Development of Design, Control, and Data Acquisition Modules for Fluid Power Education

Ms. Helene Jabbour, Purdue University

Helene Jabbour is a visiting research scholar at Purdue University's Department of Mechanical Engineering Technology. She received a bachelor's degree in mechanical engineering and applied mathematics from the American University of Beirut. Her current appointment as a scholar consists of researching and developing mechanical systems modules for some university courses within engineering technology.

Israa Azzam, Purdue University

Israa is a Ph.D. student at Purdue University, specializing in digital technologies and control systems. She received her B.S. degree in Mechanical Engineering from Beirut Arab University (BAU) in 2019 and her M.E. degree in Mechanical Engineering from the American University of Beirut (AUB) in 2021, specializing in Robust Control.

Israa is a Research Assistant on the National Science Foundation-funded Project "Research Initiation: Developing Spatial Visualization and Understanding of Complex Systems via Interactive Mixed Reality Modules". Israa leads research endeavors focusing on improving cognitive skills through extended reality (XR). Additionally, Israa's contributions extend to integrating control system analysis and design into XR, where she has developed and implemented multiple interactive Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) modules and platforms. These modules have been effectively utilized in mechanical design, training, remote operation, and engineering education. Israa has received recognition for her contributions, including the best poster and presentation awards for her work, the 2024 Bravo Award for Employee Recognition, and induction into the Honor Society of Phi Kappa Phi, placing her among the top 10% of Purdue Graduate students. Her academic journey reflects a commitment to advancing knowledge and contributing to technological innovation in XR control systems.

Her professional aspirations include applying for an Assistant Professor position upon completing her Ph.D. This career trajectory aligns with her desire to leverage her accumulated experience and knowledge to mentor and guide emerging talents. A central component of her vision is inspiring and supporting aspiring scholars in pursuing academic and professional excellence, facilitating impactful change within our field.

Ms. Isaac Elí Lago, Tecnologico de Monterrey

7th Semester Undergraduate Student for a Bachelor of Science in Mechatronics Engineering, at Instituto Tecnológico y de Estudios Superiores De Monterrey, CEM. Visiting Student Intern at Purdue University, IN.

Dr. Farid Breidi, Purdue University

Dr. Farid Breidi joined the School of Engineering Technology at Purdue University as an Assistant Professor in Aug 2020. Farid received his B.E. in Mechanical Engineering degree from the American University of Beirut in 2010, his M.S. in Mechanical Engine

Dr. Jose M. Garcia, Purdue University

Biography Dr. Jose M. Garcia-Bravo is currently an Associate Professor for the Mechanical Engineering Technology program where he has a special focus on fluid power (hydraulic systems) research and instruction, additive manufacturing and smart manufacturing using Industrial Internet of Things technologies. Garcia-Bravo received his B.Sc. in Mechanical Engineering from Universidad de Los Andes, Bogota in 2002, His M.Sc. in 2006 and Ph.D. in 2011 from Purdue University.

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Abstract

In preparing the next generation of engineering workforce, fluid power courses aim to provide students in applied engineering technology with the technical abilities industry professionals require. Within fluid power, understanding the fundamentals of pneumatic systems constitutes a core area of study due to its various applications in construction, automotive, and manufacturing. Nevertheless, traditional curricula entail limited implementation of practical knowledge in applied disciplines such as fluid power, which does not meet the expectations of a technical college or university. Consequently, students not only tend to face challenges in assimilating core fluid power concepts but are also later confronted with a lack of hands-on skills in industry. Despite the efforts to incorporate interactive tools and methods into fluid power labs, the challenge remains in training students on the control and data acquisition of fluid power systems using flexible methods that foster learning and critical thinking. Therefore, this paper presents a set of laboratory modules designed to introduce pneumatic systems design and control to fluid power college and university courses following a practical and inexpensive approach. It investigates the control of a pneumatic manipulator through an air pump and the data acquisition of a pressure transducer using an Arduino Microcontroller to measure the pressure exhibited in the system. The laboratory modules are proposed with their respective mechanical and electrical designs, hardware components, codes, and testing results.

Introduction

To meet the increasing reliance of industries on hydraulic (incompressible fluids) and pneumatic (compressed air or gas) technologies, bridging the gap between fluid power education and industry jobs' requirements becomes crucial. From manufacturing (e.g., metal forming, injection molding) and construction (e.g., lifting, digging, propulsion) to transportation (e.g., braking and power steering systems) and energy generation (e.g., hydraulic turbines in hydropower plants), fluid power applications are gradually expanding since the industrial revolution [1]. With approximately 90% of professionals in the field of fluid power working on operating machinery [2], practical hands-on experience in engineering technology education is instrumental in establishing a connection with real-world scenarios and equipping the future workforce with strong engineering foundations.

Yet, despite the prominence of fluid power applications, a limited number of colleges and universities across the U.S. offer fluid power courses or research [3] – hence, the importance of developing flexible and straightforward teaching artifacts that can be easily implemented by engineering and engineering technology programs. A key component to support teaching these topics is laboratory modules that involve the design, assembly, and testing of hydraulic and pneumatic systems. They allow students to apply counterintuitive concepts from lectures in a tangible context that fosters the learning experience [4]. Nevertheless, traditional laboratory exercises in fluid power courses are insufficient in addressing the complexity of hydraulic and pneumatic systems, resulting in relatively high withdrawals and D/F grades [5]. Thus, there is a need to incorporate innovative technologies and methods.

Previous efforts to address these challenges included the integration of digital reality technologies such as mixed reality (MR) [6] [7] and virtual reality (VR) into the laboratory work of fluid power courses [8], as well as the design of a miniature hydraulic excavator arm [9] [10] and a remote-controlled hydraulic vehicle [11] as direct applications of a fluid power course, in addition to the implementation of a CFD simulation courseware for a Gerotor pump [5].

Building on these advancements, this work addresses the remaining gap in providing modern yet easy-to-implement practices to teach instrumentation, data acquisition, control, and programming of pneumatic systems. This paper is organized as follows: The first section, "Status quo of fluid power laboratory practices in engineering technology", reviews the previous developments of fluid power laboratories and academic projects, as well as their associated learning challenges. Then, the section "Experimental setup of laboratory modules" details the setup of the fluid power-based modules that were developed with the respective experimental procedures. The section "Results and discussion of learning outcomes" expands on the implementation and testing of the developed modules and addresses expected learning outcomes. The final section, "Conclusion and future work", analyzes the results produced and contrasts them against the information reviewed from the literature and ends with suggestions for future work in this area.

Background – Status quo of fluid power laboratory practices in engineering technology

Engineering technology programs focus specifically on preparing students for direct application tasks in industry. Thus, naturally and unlike engineering courses, the detailed theoretical concepts are transcended by hands-on exercises and projects. Core skills required from a fluid power professional include running fluid power systems, understanding different components, their purpose, control functions, and techniques, designing fluid power circuits, as well as testing and interpreting system failures [2]. Educators and researchers have thus been designing and implementing laboratory practices and academic projects that focus on developing some of the skills above. Azzam et al. [11] proposed an educational demonstrator that allows students to design and experiment with a remote-controlled hydraulic vehicle in real-world tasks (Figure 1). This project reinforces students' hands-on learning experience and physical interaction in their fluid power course, while testing their inventiveness in practice through a modular approach to designing and operating the demonstrator.

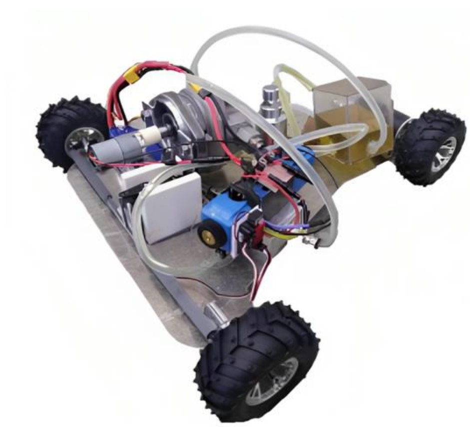

Figure 1. Modular miniature kit for a remote-controlled hydraulic vehicle [11]

Other digital interactive teaching tools included a portable excavator arm that showcases electro-hydraulic concepts in fluid power. Surveys showed a significant increase in the students' understanding of the relationship between electric and hydraulic subsystems [9]. The authors based the excavator arm design on their previous work [10], switching from applying a mechanical actuation to the arm to a hydraulic-based actuation controlled through Bluetooth and a tablet (Figure 2). Additionally, implementing CFD (Computational Fluid Dynamics) simulation courseware into laboratory work revealed an improved understanding of the operation of a hydraulic Gerotor pump and fundamentals of fluid power among students, as well as an increased engagement and interest in the lab modules [5].

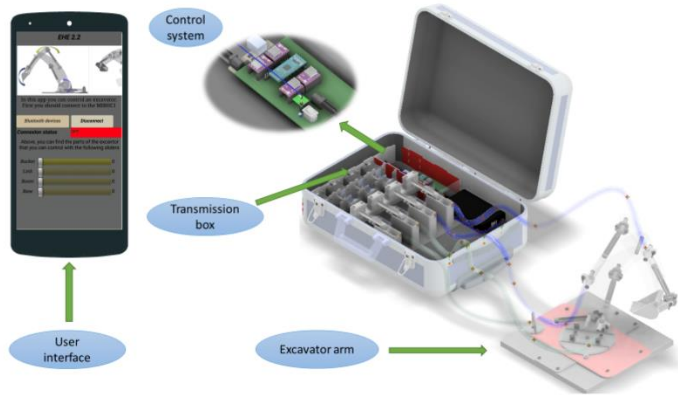

Figure 2. Electro-hydraulic excavator arm designed at Purdue University [9]

Moreover, incorporating fully immersive and interactive technologies in fluid power education constitutes a novel educational approach that facilitates the acquisition of abstract concepts through 3D visuals and real-time interaction. Through mixed reality (MR), for example, students gain a practical understanding of components, assembly, and manipulation of pneumatic and hydraulic systems such as gear pumps and relief valves [7], as well as hydraulic excavator arms [6]. In fact, researchers reported students' positive perceptions regarding integrating immersive technologies as opposed to traditional laboratories. Moreover, virtual reality (VR) refers to another branch of immersive technologies that does not offer an interaction aspect yet shows effectiveness in visualizing complex fluid power systems. In their later work on fluid power education, Azzam et al. [8] focused on integrating VR into the laboratory work of engineering technology courses to teach students about hydraulic gripper components and assembly in a construction environment.

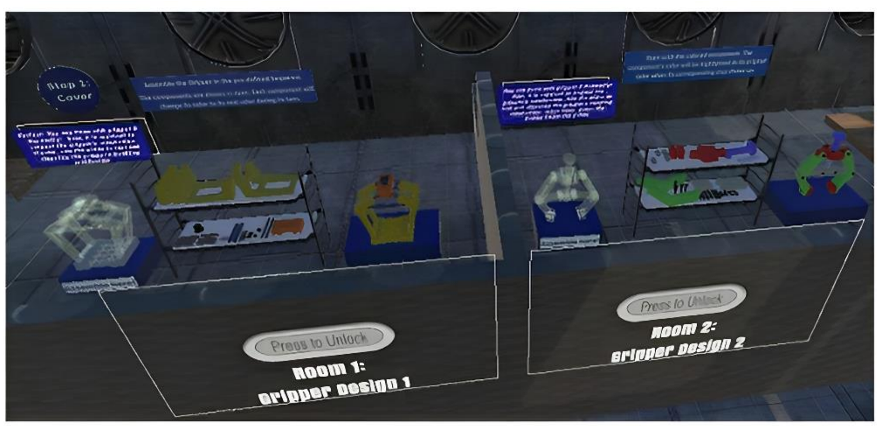

Figure 3. The hydraulic grippers in the developed VR construction-like user interface [8]

Furthermore, students shall develop solid foundations in electronics, instrumentation, data acquisition, and programming of pneumatic and hydraulic systems, as they constitute value-added skills for fluid power professionals [3]. Nevertheless, previous fluid power laboratory practices were insufficient in tackling the development of these skills in engineering technology programs. After designing a set of student-centered hands-on fluid power exercises for Purdue's Applied Fluid Power course, Shehadi et al. [12] reported an enhanced performance of students and higher confidence in using the acquired knowledge after exposure to hands-on labs. However, the authors also highlighted the lack of applications related to the design, data acquisition, and control of hydraulic and pneumatic systems and suggested future work in this area. Other researchers and educators identified this challenge and devised novel tools and methods, such as a hydraulic trainer with a digital twin to expose students to basic concepts and circuit assembly [13]. They also introduced laboratory practices and computer-assisted problem-solving exercises [14].

Moreover, it can be noted that most previous efforts for redesigning traditional fluid power labs concentrated on hydraulics systems [3], [5] - [11], [13], [15] compared to their pneumatic counterparts. An example of pneumatic work was performed by Mohit et al. [16], who designed a platform for pneumatic lab activities for a mechanical engineering technology course to introduce students to basic components such as valves, actuators, pressure gages, fittings, etc. However, the lab activities involved limited data acquisition, control, and programming exercises.

Furthermore, due to barriers such as high financial requirements and lack of storage space, real hydraulic and pneumatic systems and assemblies are generally scarcely available at engineering schools [2]. They are therefore replaced by outdated fluid power platforms that seldom integrate modern components and data acquisition systems. A key aspect of the hydraulic trainer designed by Assaf and Vacca [13] was its compact format, compared to traditional lab experiments that utilize bulky and complex test rigs like those used for research purposes. Therefore, lab kits or prototypes replicating real-world equipment constitute an inexpensive and small-scale alternative that can facilitate the integration of hands-on fluid power education at colleges and universities. These kits could be similar to those offered by some institutions for online engineering degrees [17].

As a result, new practices in fluid power education shall be incorporated in the form of laboratory kits that emphasize enhancing students' hands-on skills in the design, control, and simulation of pneumatic systems. Hence, this work suggests a set of practical modules for controlling a pneumatic manipulator using an Arduino Microcontroller and measuring the pressure exhibited in the system using a pressure transducer. The objectives of these modules include the following:

1. Preparing students to handle real-world fluid power motion control applications by learning how to control and program the opening of a gripper using a pneumatic pump and Arduino.
2. Exposing students to electromechanical hardware and circuit design used for fluid power actuation and instrumentation.
3. Guiding students in understanding and completing a light-duty gripper's mechanical design and assembly.
4. Educating students on data acquisition systems, instrumentation, and programming methods to measure pressure using a pressure transducer.

Via the lab activities, students not only learn how to manipulate a pneumatic system, but they will also be challenged to use critical thinking and problem-solving to complete the tasks (e.g., circuit design) and report the outcomes of their observations.

Experimental setup of laboratory modules

A set of three laboratory modules have been developed to meet the aforementioned learning objectives in fluid power education. Students are expected to work in groups of 3 or 4 students and deliver a report that answers specific questions for each module to test their understanding, in addition to pictures and videos of their experimental setup. The following three sections present an overview of the lab equipment utilized along with the experimental procedures to complete the lab exercises.

1. Module 1: Pneumatic gripper control and actuation

In this module, the goal is to first assemble the light-duty pneumatic gripper shown in Figure 4, then code and design an electric circuit to control the opening of the gripper. This will be achieved by controlling the system using a push button and transistor to trigger the actuation of a syringe via a mini air pump, all by using an Arduino microcontroller.

Figure 1. Final assembly of the pneumatic gripper

The design of the light-duty gripper assembly is based on a previously developed gripper in the context of enhancing construction robotics and automation [18]. The gripping mechanism consists of a syringe acting as an actuator or piston, the piston's holder connected to the gripper's arms from each side, and other mechanical components such as joints, brackets, etc. The individual components of the gripper are 3D printed from CAD models, as shown in Figure 5, and are provided for students along with the necessary screws, bolts, and syringes.

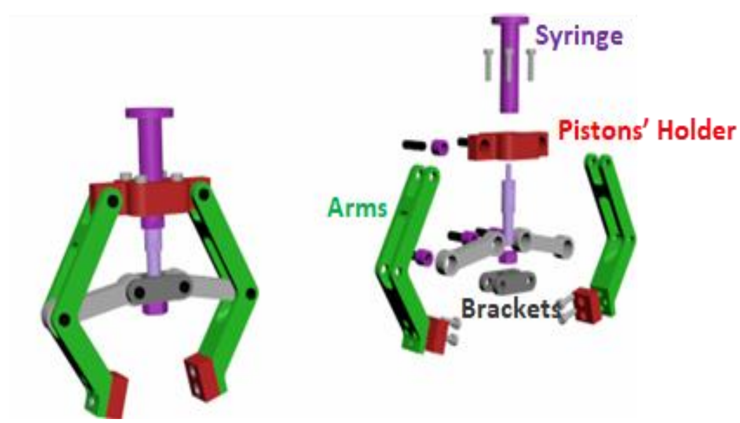

Figure 2. CAD model for a light-duty gripper

Once the final assembly of Figure 4 is completed, students will test the system by manually actuating the syringe to open the gripper. The electric circuit design responsible for controlling the gripper's actuation is then built. The circuit includes an Arduino Uno, a breadboard, a 6V DC mini air pump motor, a push button, an LED, an S8050 NPN 0.5A transistor, one kilo-ohm and 220-ohm resistors, in addition to jumper wires. All components are provided to students in the form of lab kits.

The mechanism is pneumatically actuated since it uses a pneumatic pump to extend and retract the syringe piston, which in turn applies a force on the forks of the gripper to open it. The air pump is connected to the Arduino microcontroller via an NPN transistor to control its on/off signal through the Arduino's digital pin that is controlled via the push button, i.e., without a transistor, the pump will always be on. The code to control the pneumatic pump via Arduino microcontroller is developed in the following module. The goal of the code is to turn on the air pump and the LED when the push button is pressed or turned "ON" and turn both off when the push button is unpressed or "OFF". The LED acts as a visual test to ensure the electric system is working properly. Finally, the completed assembly (Figure 6) allows one to press the push button, which turns on the air pump. The air from the pump reaches the syringe through the connected hose, leading to an increased pressure inside the syringe. The actuation of the syringe then triggers the opening of the gripper.

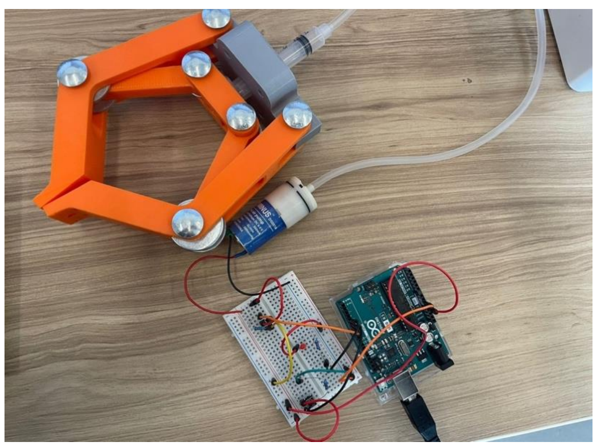

Figure 3. Final lab module output including gripper and electric circuit

2. Module 2: Instrumentation and data acquisition using a pressure transducer

The goal of this lab module consists of designing an electric circuit and developing a code in Arduino to read and display the pressure sensed by a pressure transducer. This will be achieved by integrating the sensor equation relating pressure and voltage and then displaying readings from the pressure transducer on an LCD display. The electric circuit includes an Arduino Uno, a breadboard, an LCD Display with I2C communication, a 1/8 NPT Thread Stainless Steel Pressure Transducer (0-100 PSI), and jumper wires. All components are provided to students in the lab kits. The Arduino board first powers the pressure sensor and transmits an analog signal to the microcontroller. Next, the LCD is also powered and connected to the Arduino microcontroller, enabling it to receive the pressure data to be displayed. The complete model of the electric circuit connection for the pressure transducer and the LCD is shown in Figure 7. Diagrams of electric circuits are created using "Fritzing" software, an open-source tool that allows one to develop CAD drawings to design electronics hardware [19]. Students are expected to use Fritzing to build and model the laboratory circuits as part of this exercise.

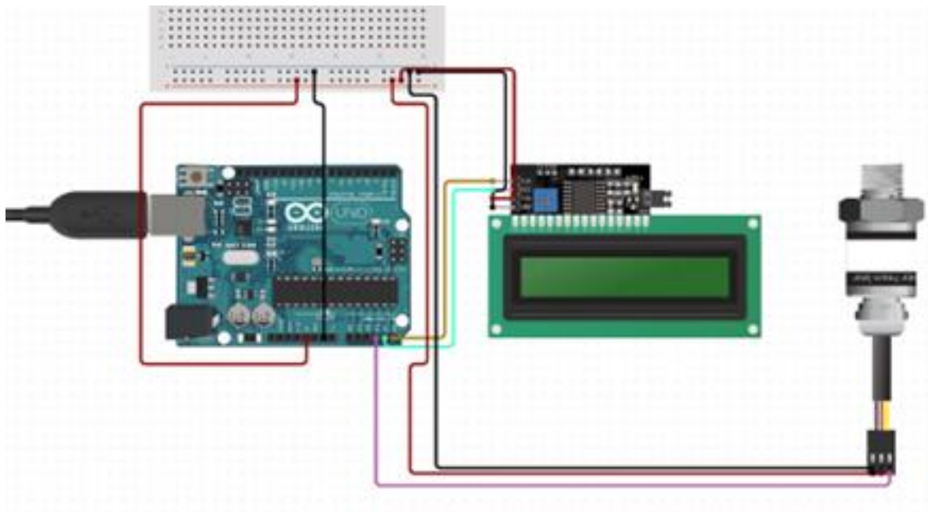

Figure 4. Complete circuit model

Subsequently, the corresponding Arduino code is developed with the first goal of converting the analog sensor signal from voltage to pressure measurements and a second goal of displaying both voltage and pressure readings on the LCD display. To allow the interfacing with the LCD screen, an I2C communication protocol was established with Arduino by downloading the corresponding libraries "LiquidCrystal I2C". An I2C communication refers to an inter-integrated circuit protocol based on a two-wire line that allows data transfer between multiple input and output devices [20]. Once the code is initialized, the analog voltage signal proportional to the measured pressure sensor can be substituted into the calibration equation obtained from the sensor's datasheet. This equation correlates the measured voltage against the measured air pressure in PSI units. The analog voltage and pressure equation is typically a function of the sensor's minimum and maximum analog voltage readings (102.4 - 921.6 units) and the minimum and maximum measurable pressure (0 - 100 PSI). For example, at 0 PSI the sensor outputs an analog value of 102.4 units, which by design of the chosen pressure transducer corresponds to 0.5 V. Similarly, at 100 PSI, the analog value of 921.6 units corresponds to 4.5 V. Arduino boards contain a 10-bit ADC (analog to digital converter) that maps the operating voltage between 0 and 5 or 3.3 V (depending on the used pin) to integer values between 0 and 1023 units [21]. Finally, the code prints the voltage output in volts on the LCD and the pressure exhibited by the system in PSI, as shown in Figure 8. To test the system, a syringe can then be connected to the pressure transducer through a hose to measure the pressure change due to the actuation of its piston.

Figure 5. Voltage (Volts) and pressure (PSI) displayed on the LCD

3. Module 3: Pressure measurement at a pneumatic gripper using a pressure transducer

This third module aims to combine modules 1 and 2 to measure the pressure exhibited at the pump and pneumatic gripper using the pressure transducer and display it on an LCD screen. In addition, a pressure gauge is incorporated into the pneumatic system to benchmark the pressure readings displayed on the LCD. For this purpose, a compact lab kit is supplied to students, including all necessary components from previous modules such as the assembled gripper with the syringe, hoses, a mini air pump, a transducer with the necessary fittings, a breadboard, Arduino Uno, in addition to other electronic components such as resistors, transistor, jumper wires, a LED, and a push button.

The combined electric circuit of the first two modules is built using one Arduino microcontroller to power and transfer data to and from the LCD, the pump, and the pressure transducer. Once the electric subsystem is completed, a 3-way pneumatic subsystem is built by connecting the pressure transducer with the pump and the syringe of the gripper using a Tee fitting. It is essential to ensure minimal air leaks and secure connections in the pneumatic subsystem –all NPT threads used about one or two turns of Teflon tape. Additionally, the syringe shall be cleaned and returned to its original state before recording measurements. The final system, including both electrical and pneumatic subsystems, is showcased in Figure 9 using Fritzing software.

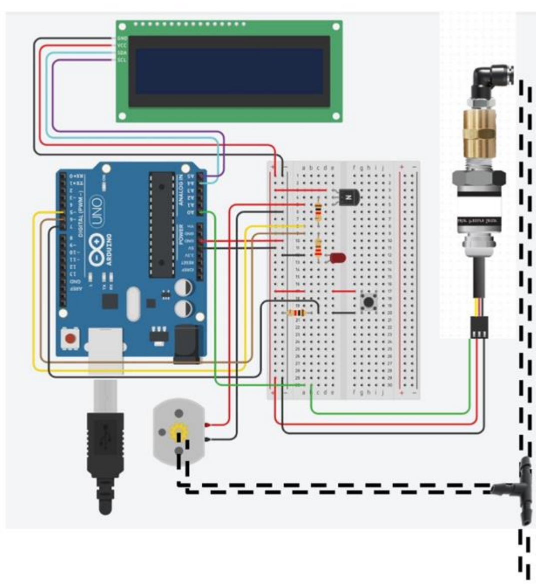

Figure 6. Complete system model

As a next step, an Arduino code is developed to turn on the pump when the push button is pressed, then convert analog pressure transducer measurements to pressure readings and display them on the LCD screen. The codes developed in modules 1 and 2 are used as a starting point for module 3 code, while ensuring that the Arduino microcontroller's appropriate analog and digital pins are updated based on the new combined circuit. Finally, to test the pressure measurements of the transducer, a pressure gauge is integrated in series with the pneumatic subsystem using the appropriate hoses and fittings. In the final working system shown in Figure 10, when the push button is on, the pneumatic gripper opens; consequently, pressure and voltage readings are displayed on the LCD screen, and pressure can also be recorded from the pressure gauge board.

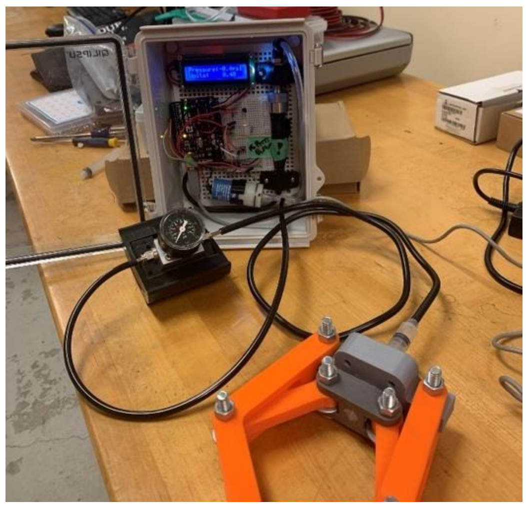

Figure 7. Working system for pressure readings on LCD screen and pressure gauge

Discussion and learning outcomes

The main purpose of this set of laboratory modules is to bolster engineering technology students' understanding of the design, control, and data acquisition of pneumatic systems. Not only does it cater to hands-on practice in fluid power education, but it also allows flexible and inexpensive implementation in existing curricula via compact lab kits. Module 1 introduces students to the mechanical assembly of a light-duty gripper and helps them gain an understanding of the actuation and control of a pneumatic gripper using an air pump. Then, module 2 educates them on the instrumentation techniques to record pressure measurements using a transducer and the establishment of I2C communications to handle LCDs. Finally, module 3 constitutes a consolidated implementation of learnings on pneumatic systems. It denotes resulting observations on the actuation of the gripper and the measured pressure using the transducer while benchmarking the sensor measurements against readings from a pressure gauge. Furthermore, student-centered lab reports have been developed for each module to provide guidance as well as to test students' understanding of fundamental fluid power concepts throughout the exercises. The lab reports ask students to describe the mechanical operation of a pneumatic setup, list the various components required to operate a standard pneumatic power system and assess and review the advantages and potential applications of the system. Students shall report their observations, address the lab report questions, and provide visual support in the form of pictures and electric circuit diagrams designed in Fritzing. Therefore, students acquire multiple overarching learning outcomes and practical skills, including technical writing, mechanical assembly, manipulation of electromechanical hardware and microcontrollers, programming, drawing of circuits in Fritzing, data acquisition, instrumentation, etc.

Conclusions and Future Work

The proposed work showcases a set of three laboratory modules designed to introduce pneumatic systems design and control to fluid power courses in engineering technology. The modules complement previous efforts to foster hands-on learning in fluid power education by reinforcing technical abilities related to the control, data acquisition, and instrumentation of pneumatic systems, among other programming and hardware manipulation skills. They prepare students to handle real-world fluid power motion control applications by learning how to assemble, control, and program the opening of a gripper and extract data using a pressure transducer. These laboratory practices designed as compact lab kits constitute a flexible, easy-to-implement, and inexpensive solution to replace bulky and expensive fluid power setups. The set shall be further expanded by introducing modules for sensor calibration and pneumatic lifter design, for instance, then incorporating the full modules into fluid power engineering laboratories. Subsequently, future work will focus on assessing the effectiveness of these laboratory exercises by evaluating students' understanding of the targeted concepts through surveys.

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