The EHE arm shows evidence that hands-on resources and activities like the one presented herein can improve students' understanding of fluid power concepts and create linkages to real-world applications of the technology.

electro-hydraulic excavator 2.2:

fundamental concepts in fluid power

by Camilo A. Zorro-Mendoza, Jorge A. Leon-Quiroga, Brittany A. Newell, and Jose M. Garcia-Bravo

Introduction

The essential elements of engineering, science, and technology begin to take shape in middle school through the teaching of curriculum focused on STEM (Guzey et al., 2016). However, this process can be hindered by low student interest, which has resulted in a decrease in the number of students planning to pursue STEM careers such as engineering and engineering technology in recent years (Kim, 2018). The enrollment crisis has become such a critical situation that in 2018 Elsevier determined that making STEM more appealing to young students was identified as one of the great challenges of engineering (Elsevier, 2019).

A key element for overcoming this challenge is the development and implementation of hands-on practices such as Project-Based Learning as a fundamental element for making STEM careers more appealing to young students. Several researchers have proposed activities, including pedagogical improvements for the teaching process (Choudhury, Ikonomov, Rodriguez, & Ramrattan, 2008), workshops for K-12 students (Garcia, Kuleshov, & Lumkes, 2014), robotic arms, and various other experiential initiatives (El Tiempo, 2018). In this work, we introduce a curricular activity for an exceptionally challenging STEM topic, fluid power.

Figure 8. Mobile app and final product assembly.

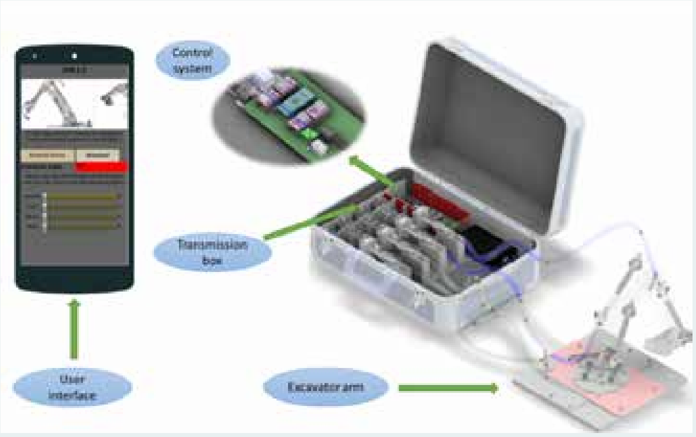


Figure 1. Electro-Hydraulic Excavator arm 2.2.

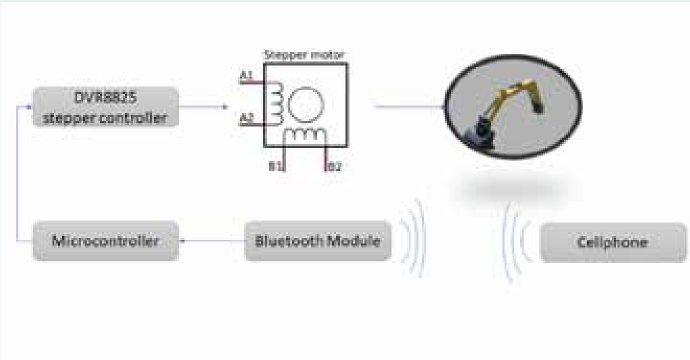


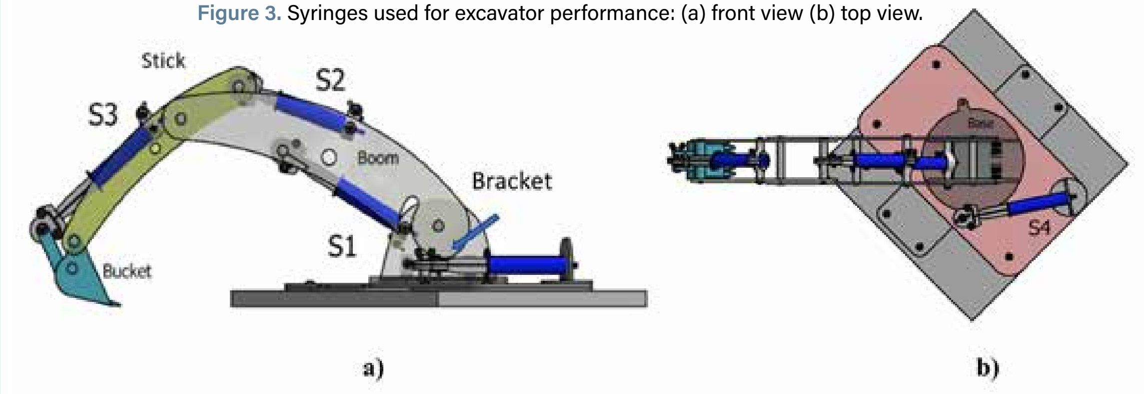
Figure 2. Control schematic.

The fluid power industry has a significant skills and gender gap, with fewer people pursuing fluid power careers compared to those leaving due to retirement. Based on an industry survey in 2017 conducted by the *Fluid Power Journal*, 95.4% of those people who identified themselves as having a fluid power career were male, and 4.6% identified as female (*Fluid Power Journal*, 2017).

Researchers at Purdue University (Garcia et al., 2014) created a portable fluid power demonstrator for attracting the interest of middle and high school students to STEM careers (Mishler et al., 2011). Their demonstrator and accompanying activities demonstrated Pascal's law, an essential fluid power and engineering concept, by installing cylinders of various bore sizes in a toy excavator. This first-version demonstrator has been used for teaching fluid power for in-person workshops with diverse audiences (Garcia et al., 2014). The demonstrator is a small-scale excavator arm build-up with small linear pneumatic actuators, paired with a set of four 4/3 pneumatic directional control valves, a steel frame, and compressed air or water as a working fluid. The activities used to accompany this version of the demonstrator involved not only fluid power topics, but also showed the operating principles for control of solenoid valves through programmable logic controllers and the movements performed for the joint action of valves and pneumatic actuators.

Noncurricular activities and projects like the demonstrator described above or the fluid power challenge produced by Rogers (Rogers, 2013) can be used to introduce young learners to a specific technical area at a fundamental level and can have a larger impact by reducing barriers to entry if they can be implemented with low budgets, requiring less complicated materials and more practical activities. The present work displays a new excavator arm version called the Electro-Hydraulic Excavator 2.2 (EHE), where the main goal is still to show learners a fundamental concept in fluid power, Pascal's Law, as well as new electronics and programming concepts that are implemented for controlling the mechanical elements, including Bluetooth control via a mobile phone application. This article describes three main elements of the implementation of this project: (1) The redesign and implementation of the excavator arm is presented in the Excavator Arm and Design Process section, (2) The implementation of the excavator and laboratory activities to use it are presented in the EHE Implementation in the Fluid Power Laboratory section, and (3) The assessment tool to measure the impact of the arm and activities is shown in the Results and Discussion section. These sections are followed by the presentation of the results, also in the Results and Discussion section, and concluding remarks in the Conclusions section. To assess the performance of the EHE arm, a laboratory guide for the students was designed as well as pre- and post-surveys intended to collect their opinions, impressions, and any existing preconceptions regarding the general topic of fluid power. The final product of this project was a fully assembled portable excavator arm, using a low-cost design that allows instructors to have an easy-to-transport and cost-effective tool, as well as to improve students' perceived understanding of fluid power concepts and applications.

Figure 3. Syringes used for excavator performance: (a) front view (b) top view.



Excavator Arm and Design Process

Before the EHE presented here was designed, two early versions were built with four main subsystems: the excavator arm, the transmission box, the control system, and the user interface. EHE 2.2 builds upon those systems as seen in Figure 1, and consequently four sections for improvement were established as the base for the redesigned version. Figure 2 shows a diagram of the control system used to electronically operate the excavator arm.

A. Mechanical Improvements

Using a miniaturized version of an excavator is a proven method for providing real-world context for learners being introduced to the topic of fluid power (Garcia et al., 2014). Previously developed excavator arms were successful at demonstrating the relationship between pressure and force through a piston area. However, the components used in the earlier excavator arms were sensitive to contamination and locked up over time. The arms were also large and not very portable. The system also did not allow for interchangeable piston sizes, which hindered students from experimenting with the effects of bore area on the pressure-force relationship. The new excavator arm presented here makes use of a 4-bar linkage to perform its movements. Syringes S1, S2, and S3 produce the movement of the bucket connected to the stick and syringe S3; the stick is operated by the actuation of syringe S2; and the boom is operated by the actuation of syringe S1. Those three movements produce a 2D (in-plane) displacement of the bucket, which allows the system to reach a horizontal distance of 407 mm and a height of 303 mm. Lastly, syringe S4 is used to control the rotational movement of the arm, which allows it to achieve an angular displacement of 45 degrees as seen in Figure 3.

The improvements of the EHE 2.2. were focused on two aspects: the angle of rotation for syringe S4, and the height of the bracket where syringe S1 is supported. In a past version of the excavator EHE 2.0, the hose connector for lifting the arm tended to drag, causing the entire arm to become disconnected and be nonoperational. Similarly, it was found that the rotation point where the arm was mounted was insufficient for accommodating the actuation of the swing movement. This movement was challenging to produce due to friction and low clearance. Therefore, the solution required drilling bigger holes that allowed for addition of bushings, as shown in Figure 4. The second design improvement was the increased height of the mounting brackets attaching the arm to the base as seen in Figure 5. This improved the hose connection space and therefore avoiding bending of the hoses. These modifications were found to be beneficial because they improved the fluid flow to the actuation pistons (syringes) and produced a smooth swing movement of the arm. These modifications also reduced friction points that continuously loosened the bolts that joined the various sections of the arm.

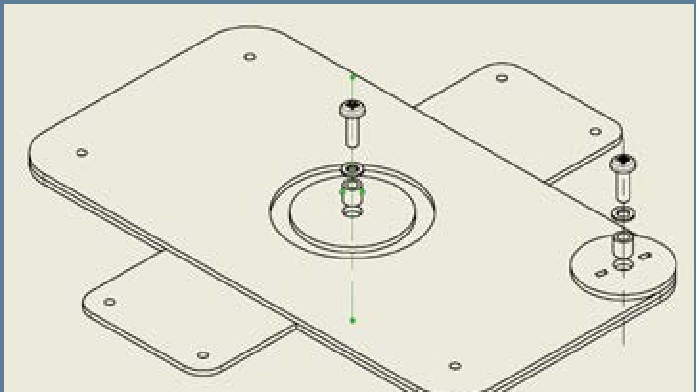


Figure 4. Bushings for arm base.

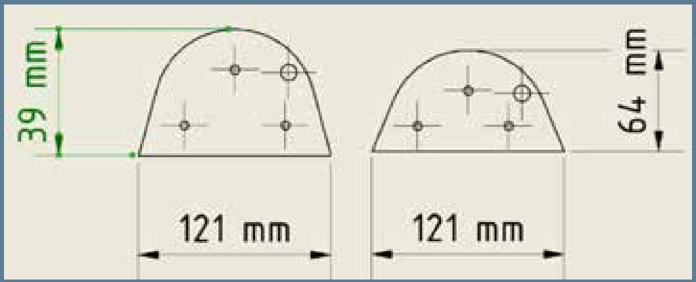


Figure 5. Base bracket. New version (right) old version (left).

	Symbol	Value [N]		Symbol	Value [Deg]
Bucket weight	W_{Bu}	1.35	Angle of force F1	α	60
Stick weight	W_{L}	0.62	Angle of force F2	ß	71.38
Boom weight	W_{Bo}	0.86	Angle of force F3	Γ	40.09

Table 1. Weights of elements angle of forces.

Distance	Value [mm]	Distance	Value [mm]	Distance	Value [mm]	Distance	Value [mm]
a	110.67	*d*	371.70	*g*	58.31	*j*	2.09
b	157.87	*e*	69.88	*h*	110.65	*k*	29.96
c	287.15	*f*	26.10	*i*	29.79	*l*	10.56

Table 2. Distance from pivot points to forces.

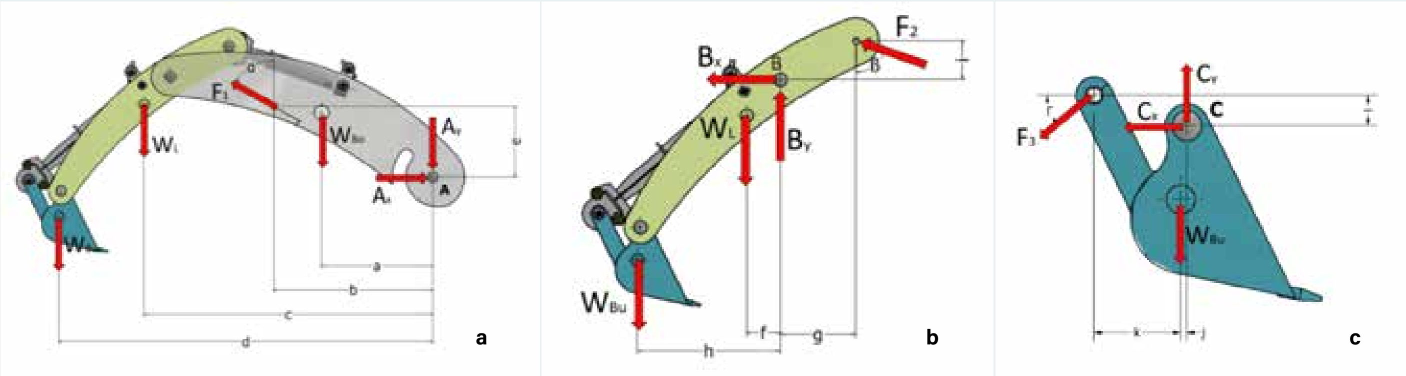


Figure 6. Free-body diagram of the mechanism: (a) bucket [blue], boom [yellow] and stick [grey] element; (b) boom [yellow] and bucket [blue] element; and (c) bucket element.

$$\sum M_A = 0 \rightarrow -bCos(\alpha)F_1 + eSin(\alpha)F_1 + aW_{Bo} + cW_L + dW_{Bu} = 0 \rightarrow F_1 = \frac{-(aW_{Bo} + cW_L + dW_{Bu})}{eSin(\alpha)F_1 - bCos(\alpha)F_1}$$

Equation 1. Sum of moments for free-body diagram, Figure 6a.

$$\sum M_B = 0 \rightarrow gCos(\beta)F_2 + iSin(\beta)F_2 + fW_L + hW_{Bu} = 0 \rightarrow F_2 = \frac{-(fW_L + hW_{Bu})}{gCos(\beta) + iSin(\beta)}$$

Equation 2. Sum of moments for free-body diagram, Figure 6b.

$$\sum M_C = 0 \rightarrow lCos(\gamma)F_3 + kSin(\gamma)F_3 + jW_{Bu} = 0 \rightarrow F_3 = \frac{-(jW_{Bu})}{lCos(\Gamma)F_3 + kSin(\Gamma)}$$

Equation 3. Sum of moments for free-body diagram Figure 6c.

$$T_R = \frac{Fd_m}{2} * \frac{l_e + \pi f_r d_m \sec(\theta)}{\pi d_m - f_r l_e \sec(\theta)}$$

Equation 4. Torque required for the lead screw.

B. Motor Selection

For the selection of the electric motor and the transmission system needed to electronically operate the arms, a kinematic analysis was done based on the EHE free-body diagrams shown in Figure 6. From these diagrams, three equilibrium moment arm equations were established, through which the various syringe forces were obtained as shown in Equations 1, 2, and 3. The free body diagrams presented in Figure 6 are essential for establishing the equilibrium equations, a fundamental physics concept in science and engineering. By looking at these components, the students can understand how the math equations are useful in a real-life application. The weight of the bucket, boom, and stick were considered and the pivot point for the sum of moments was located at Point A. This free body diagram was used to determine the force needed to move the whole arm with Syringe S1 shown in Figure 2. As a result, Equation 1 was obtained (see Figure 6a and Equation 1). In the same way, Equation 2 was formulated based on the free body diagram shown in Figure 6b where the pivot is located at Point B. Lastly, Equation 3 was found using the sum of moments for the bucket member shown in Figure 6c. For this free body diagram, the pivot is located at Point C.

Equations 1-3 were expressed as a function of the parameters shown in Table 1 where, W_{Bu}, W_L, and W_{Bo} are the weight of bucket, stick, and boom of the arm respectively; α, β, and Γ are the angles of the line of action of syringes S1, S2, and S3 respectively; a, b, c, and d are the horizontal distances from pivot A to forces W_{Bo}, F_1, W_L, and W_{Bu} respectively; e is the vertical distance to F_1; f, g, and h are the horizontal distances from pivot B to W_L, F_2, and W_{Bu} respectively; i is the vertical distance to F_2; j, and k are the horizontal distances from pivot C to W_{Bu}, and F_3, respectively; l is the vertical distance to F_3; F_1, F_2, and F_3 are the torque values needed to push syringes S1, S2, and S3. The resulting values and assumptions are shown in Tables 1, 2, 3 and 4.

	Symbol	Value
Mean diameter	d_m [mm]	7
Lead	l_e [mm]	8
Coefficient of friction (Sahin, De Pauw, Sukumaran, & De Baets, 2015)	f_r	0.44
Thread angle	θ	20

Table 3. Lead screw parameter.

	Force	Value [N]	Torque	Value [N·mm]
Syringe 1	F1	42.27	T_{R1}	148.37
Syringe 2	F2	3.54	T_{R2}	1 2.43
Syringe 3	F3	0.10	T_{R3}	0.36

Table 4. Force and torque on the syringes.

A transmission system using a lead screw paired with an electric stepper motor was used to ensure accurate displacement of the syringe piston. The selection of the stepper motor was based on the torque needed to apply the forces calculated in Table 4. The following equation was used to guide the selection process.

In Equation 4, above, d_m is the mean diameter of the screw, l_e is the lead of the screw, f_r the dynamic coefficient of friction between POM and steel, and θ is the thread angle. (Budynas & Nisbett, n.d.). Table 4 shows the torques T_{R1}, T_{R2}, and T_{R3} needed to push syringes S1, S2, and, S3 respectively. The stepper motor selected was a Usongshine Nema 17HS4401, which has a maximum torque of 400 N·mm. The maximum torque required for the stepper motors is 148 N·mm as is shown in Table 4.

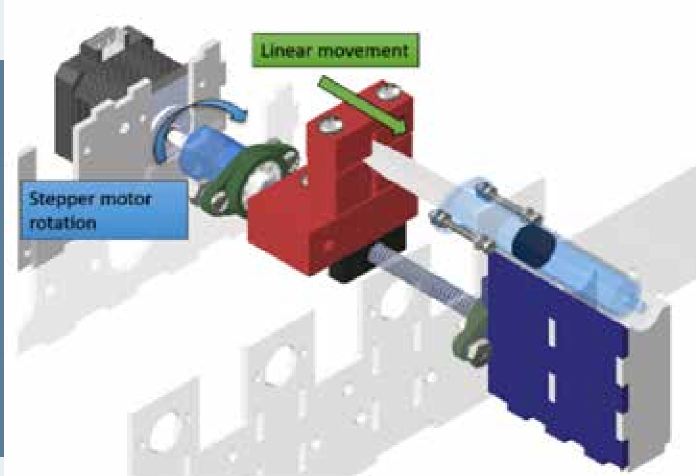


Figure 7. Stepper motor movement.

C. Control Design

A stepper motor driver, a microcontroller, and the communication protocol to control the motor were selected to operate the arm. These components were selected after a review of the existing options. In the case of the driver, the DRV 8825 driver was selected because it permits control of the stepper motor in bipolar mode (bidirectional), and it has two inputs that control its steps and direction. This was necessary for operation and retraction during the excavator movement.

A wireless communication protocol was desired to operate the arm. The Bluetooth communication protocol was selected because it is ubiquitous and can accomplish this requirement. Hence the HC-06 Bluetooth module was chosen for this purpose. For the microcontroller, a controller that was simple to program and commonly available was necessary. The microcontroller also needed to operate four stepper motors separately and at the same time. The Arduino Mega 256 was selected for this propose. Figure 2 shows a schematic of the control of the stepper motors used to turn the lead screws for pushing the syringes.

An Arduino code was implemented to control the different actuators of the EHE arm. Examples of this code are shown in Figure A1 and A2 in Appendix 1, and the full flowchart of the programming logic is depicted in Figure A3 in Appendix 1.

The code starts with the data variable that is obtained via the Bluetooth module. The value is received, and the program gives the instruction that determines the direction of rotation. Then, the number of the steps needed to make the movements are determined as seen in Figure A4 in Appendix 1.

The stepper motor, which is coupled to a lead screw, produces a linear motion to push the syringe piston seen in Figure 7. Performing those movements allows for the displacement of water inside the syringes to push the plunger, which is connected to the mechanism on the excavator. This mechanism was replicated four times to perform the desired movement of each element of the arm (base, bucket, stick, or boom).

D. User Interface

For this stage of the project, the MIT Inventor application (Patton et al., 2019) was used. This open source software, which can be found online, allows the user to program and develop simple applications in a short time frame. For this project, it was used to create a graphical user interface for the control of the EHE arm. This system permits users to operate the system with a phone fitted with a Bluetooth communication module. The application allows the user to send desired commands to control the movements of the arm. An image of the application is depicted on the left pane of Figure 8 (page 1). Lastly, portability is a key feature to achieve wide replication and deployment of this kit. Therefore, the arm elements were designed to fit in a standard aluminum case to enable easy packing and transportation.

EHE Implementation in the Fluid Power Laboratory

The impact of the second objective of this study was to assess the impact of the EHE arm in the classroom. Two surveys were implemented in a class of nearly 90 students to measure the perceived value of the activity on their learning. The survey questions can be found in Appendix 2.

E. Presurvey Testing

In this first stage, five replicas of the excavator arm were trialed in an introductory college fluid power course. A pre-laboratory survey (see Appendix 2 for survey questions) was given to the students enrolled in the fluid power class before they used the EHE arm. This survey was composed of several statements where students rated their agreement with each. These statements were answered using a Likert scale (strongly disagree, somewhat disagree, neither agree nor disagree, somewhat agree, or strongly agree). The first four questions were used to assess how much confidence participants had in their knowledge of basic principles in fluid power, and the last statement evaluates their understanding of Pascal's Law, a basic concept in fluid power. The survey ended by asking the students to list three applications of fluid power, which were used

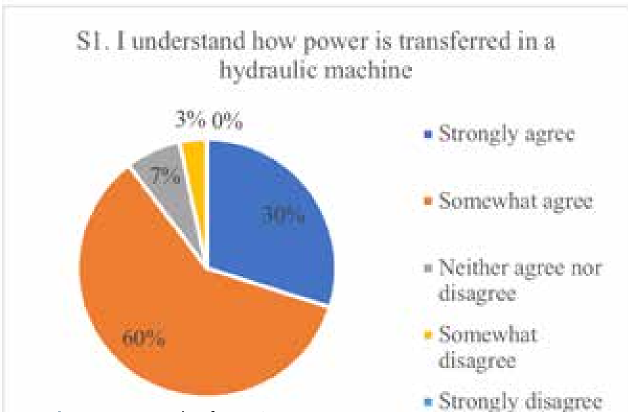


Figure 9. Results from Statement 1.

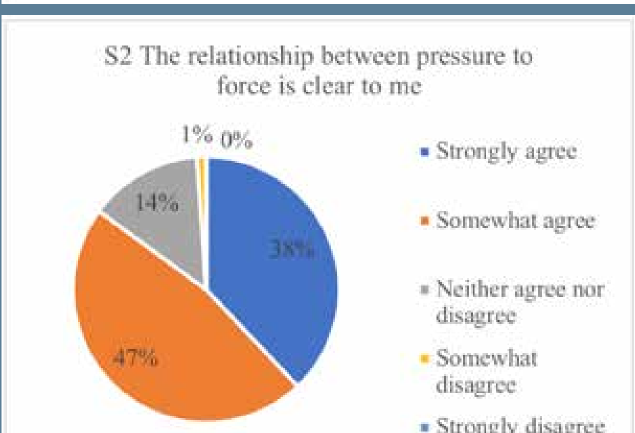


Figure 10. Results from Statement 2.

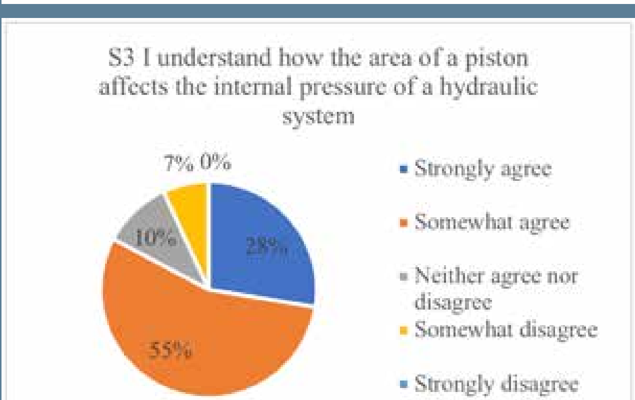


Figure 11. Results from Statement 3.

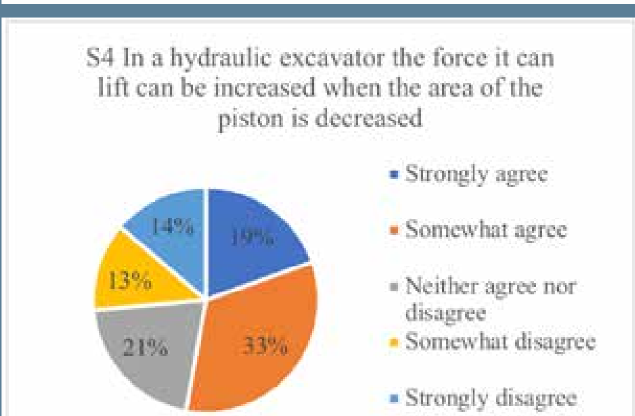


Figure 12. Results from Statement 4.

to assess how students connect the principles covered in the first two lectures with real-world applications using similar systems.

F. Lab Activity

Once the first survey was completed by the students, the hands-on activity was implemented following the laboratory guide (see Appendix 4) and was composed of two main sections, *Operation* and *Reflection*. The first displays the nature of *Making and Doing* practice, per the definition of *Standards for Technological and Engineering Literacy* (*STEL*) (ITEEA & CTETE, 2020). This was put in practice by the students when they were asked to describe the performance of the excavator arm from a qualitative perspective using different syringe sizes. Then, they were asked to take piston displacement measurements and measure voltage and current on the stepper motors of the EHE arm with a multimeter. These measurements were needed to back-calculate the forces and pressure inside the system as well as the electrical and mechanical power required to move the arm (quantitative measures).

Finally, the *Reflection* section was assigned to the students, asking them to think about how the piston displacement and the magnitude of the forces would change in the system with different syringe sizes, how the electrical and mechanical power consumed are related to each other, and how the arm fitted with hydraulic components can be controlled with electronic devices. Regarding this, three core disciplinary standards from *STEL* were addressed. First, with Questions 1, 2, 4, and, 5, the students identified how electrical and mechanical power work and how it is distributed through the whole system, which is related to *STEL* Benchmark 1N: *"Explain how the world around them guides technological development and engineering design."* (ITEEA, 2020). Likewise, Questions 3 and 7 are targeted at improvement and design processes based on observations, which is in line with Benchmark 1R: *"Develop a plan that incorporates knowledge from science, mathematics, and other disciplines to design or improve a technological product or system."* (ITEEA, 2020). Lastly, Question 6 encourages students to analyze and identify the elements that allow them to control the EHE arm, complying with *STEL* Benchmark 2V: *"Analyze the stability of a technological system and how it is influenced by all the components in the system, especially those in the feedback loop."* (ITEEA, 2020).

G. Post-Survey

As a final stage of the evaluation process, a post-survey was given to the students using the same questions and rating scale used in the presurvey. The purpose of the post-survey was to evaluate the students' perception of their learning process after conducting the lab, and how the tool used for teaching enhanced their own understanding of Pascal's Law and its relationship with a real-life application.

Results and Discussion

H. Redesigned Arm

A hydraulically operated excavator arm controlled by syringes was designed and built. It was driven by a combination of stepper motors and a lead screw transmission. This allowed for precise movement of the arm and allowed for transformation of the rotational movement into linear motion driving the syringes to operate the segments of the arm. The prototype was fitted with Bluetooth serial communication with a range of 9 meters, even with physical obstacles between the mobile device and the Bluetooth module, and 39 meters in a clear line of sight. A horizontal range of 407 mm, a vertical range of 303 mm, and a rotation of 45 degrees were achieved with the excavator arm.

The EHE device can be controlled through a mobile application that provides commands to the microcontroller and then the stepper motor, with steps having a resolution of 1.8 degrees per step, allowing for precise control during device operation. Other advantageous features of this device are its portability and energy efficiency. The device uses a 6800 mAh and 12 V DC battery. Its average consumption is 1.7 A per actuator. It weighs 7.8 kg, which makes it easily transportable, especially in comparison to the original version of the arm which weighed 35 kg.

I. Laboratory Activities

The presurvey provided a total of 87 responses. The students were asked how confident they felt about their knowledge and if they understood concepts like power transfer in hydraulic machines, the relationship between pressure and force, internal pressure of hydraulic systems, and the relationship between current and force.

In the first three presurvey statements above, Figure 9 shows that 10% of the students do not understand how the power is transferred by the hydraulic system, Figure 10 shows that 15% of them do not understand the force and pressure relation, and Figure 11 shows that 17% did not understand how the area affects the internal pressure of the system.

This shows that most of the students have some basic ideas about the hydraulic systems and the concepts of force, pressure, power, and relationship between them. But, in Statement 4, it seems that fewer than half of the students (48%) understand the concept related to Pascal's Law (Figure 12).

In addition, the last statement depicted in Figure 13 shows that 44% of the students had no previous knowledge of concepts regarding the relationship between force and current. This demonstrates an opportunity to use tools like the EHE arm in order to demonstrate energy flow and the relationship between electric and hydraulic power.

On the other hand, the Word Cloud shown in Figure 14 shows which applications students connect with fluid power systems; most notably, braking systems, excavators, and suspension systems were associated with fluid power applications. This shows what real-world linkages students see and provides ideas for other hands-on device applications.

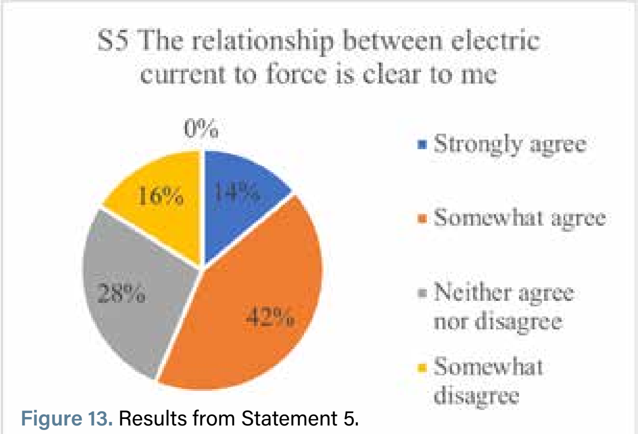


Figure 13. Results from Statement 5.

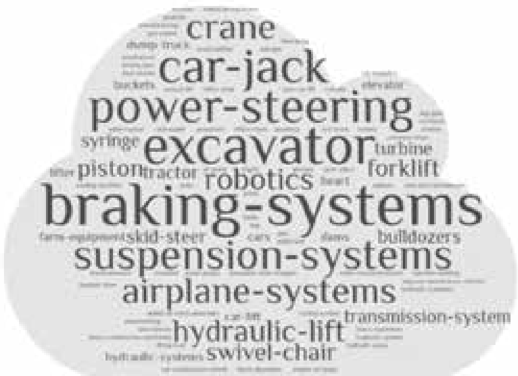


Figure 14. Word Cloud of the fluid power applications.

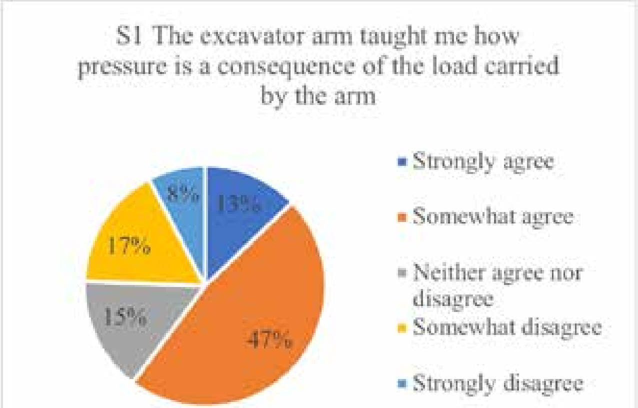


Figure 15. Results from Statement 1.

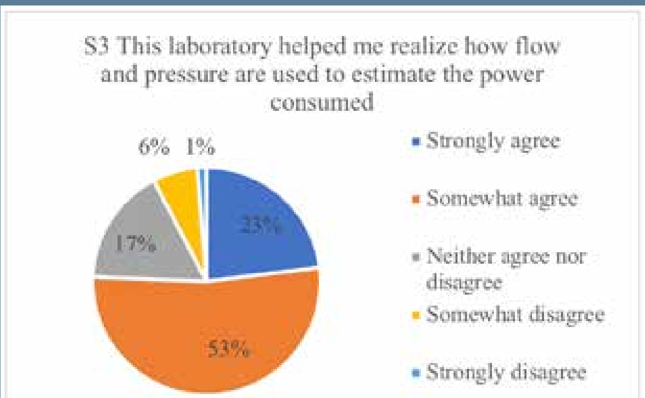


Figure 16. Results from Statement 2.

After the lab experience, students' impressions were recorded with a post-survey. A total of 78 of the original 87 students returned their survey responses. The responses show students' perception as to how the activity helped them increase their knowledge during the learning process.

As shown in Figure 14, 60% of students claimed they understood the relationship of pressure and load after using the EHE. While most students linked the two concepts correctly, improvements could be made to highlight this concept during the lab experience to advance student learning. Nevertheless, the concept of Pascal's law was illustrated with the excavator when the students were asked to reflect on the effect of changing the syringe sizes. According to the survey data shown in Figure 15, 79% of students thought they understood how the area of the pistons was a key factor in the design of powerful machines. Also, as is shown in Figure 16, 76% of the students agree that the excavator was helpful to determine the power consumption of the system.

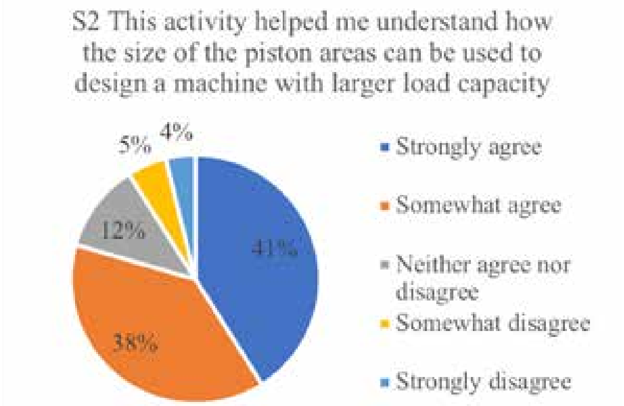


Figure 17. Results from Statement 3.

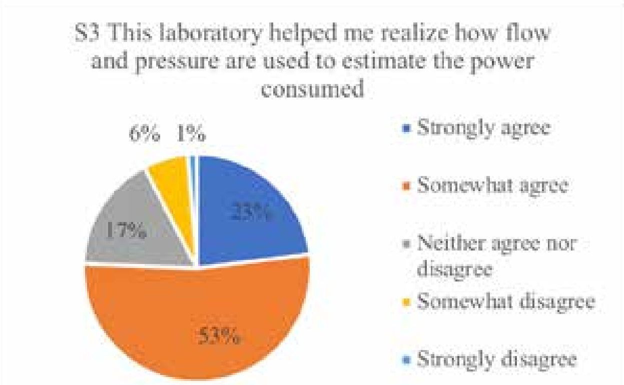


Figure 18. Results from Statement 4.

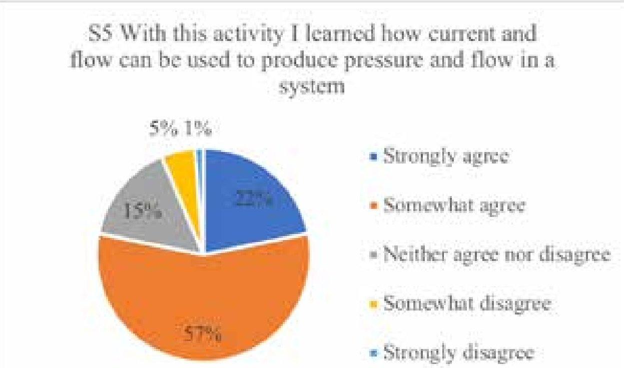


Figure 19. Results from Statement 5.

Finally, the last two survey statements show the excavator arm was helpful for teaching the relationship between mechanical and electrical power. Eighty-two percent of the students agreed with Statement 4 (Figure 17). This is an encouraging result considering that, in Statement 5 of the presurvey, half of the students did not have a clear idea of how electrical current was related to mechanical force. In the same way, Statement 5 (Figure 18) shows that the students identify a relationship between the current consumed and the pressure produced in the system after the hands-on experience.

Conclusions

As presented in this document, a new functional compact prototype was designed and built to teach fluid power concepts in a hands-on format. The accompanying curriculum involves various engineering concepts such as pressure, flow, Pascal's law, statics, mechanical and electrical power, and the relationship between mechanical and electrical variables. These concepts were presented to students with the goal of increasing their understanding and enhancing their interest in fluid power by facilitating their understating of the relationships between fluid power concepts and the real world.

The EHE arm was evaluated using pre- and post-surveys to assess the effectiveness of the arm and the accompanying laboratory activities in improving perceived student learning and its usefulness in the early stages of a fluid power class and other early college, middle, and high school STEM settings. In general, based on students' responses, the activity improved their perceived understanding of fluid power concepts and applications. This is reflected in the post-survey where 79% of the students declared they understood the relationship between the area of a piston and the load capacity, 76% thought that the arm helped them to understand how the fluid's pressure and the power consumed were related, 82% found the arm was a useful tool to explain the relationship between mechanical an electrical power, and 79% learned about the use of electrical current in the control of hydraulic systems.

However, the concept of fluid pressure itself seems to be unclear for the students; 40% of them disagree according to the responses given in Statement 1 of the post-survey. Alternative methods of explaining this concept should be considered in future work. In summary, the EHE arm shows evidence that hands-on resources and activities like the one presented herein can improve students' understanding of fluid power concepts and create linkages to real-world applications of the technology.

Acknowledgements

This research was supported in part by the National Fluid Power Association, Universidad Nacional de Colombia, and Purdue University.

References

Bakker, B. de. (2019). *Stepper motor with DRV8825 and Arduino tutorial* (4 Examples). Retrieved from Makerguides website: www.makerguides.com/drv8825-stepper-motor-driver-arduino-tutorial/

Budynas, R. & Nisbett, K. (2021). *Shigley's mechanical engineering design* (10th ed.). New York: Mc Graw Hill.

Choudhury, A., Ikonomov, P., Rodriguez, J., & Ramrattan, S. (2008). *Multi-mode learning and fluid mechanics to fluid power: An undergraduate curriculum reform.* Conference Proceedings, ASEE Annual Conference and Exposition.

El Tiempo. (2018). *STEM Education for the future* (educación para el futuro). Retrieved from www.eltiempo.com/archivo/documento/CMS-16540819%0A

Elsevier. (2019). *10 major engineering challenges of the next decade.* Retrieved from Empowering Knowledge website: www.elsevier.com/rd-solutions/industry-insights/other/10-major-engineering-challenges-of-the-next-decade

International Fluid Power Society. (September, 2017). 2017 Salary survey. *Fluid Power Journal, 24*(8). https://issuu.com/idpcreative/docs/fpjso17_e?e=1863291/52680390

Guzey, S. S., Moore, T. J., Harwell, M., & Moreno, M. (2016). STEM integration in middle school life science: Student learning and attitudes. *Journal of Science Education and Technology, 25*(4), 550-560.

Mishler. L., Garcia, J., John H Lumkes. (2011). *Engaging pre-college students in engineering using hands-on micro-processor controlled portable fluid power demonstrators.* In American Society of Agricultural and Biological Engineers, Louisville, Kentucky, August 7-10, 2011 (Vol. 7004, p. 11). St. Joseph, MI: ASABE. http://doi.org/10.13031/2013.38120

Garcia, J. M., Kuleshov, Y. A., & Lumkes, J. H. (2014). *Using fluid power workshops to increase STEM interest in K-12 students.* Conference Proceedings, ASEE Annual Conference and Exposition, Indianapolis.

International Technology and Engineering Educators Association (ITEEA). (2020). *Standards for technological and engineering literacy: The role of technology and engineering in STEM education. Executive summary.* Reston, VA: Author.

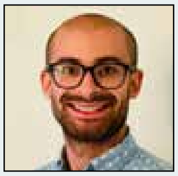
Kim, S. (2018). *New research shows declining interest in STEM.* Retrieved from Centre for Digital Education website: www.govtech.com/education/k-12/New-Research-Shows-Declining-Interest-in-STEM.html

Patton, E. W., Tissenbaum, M., & Harunani, F. (2019). MIT app inventor: Objectives, design, and development. In *Computational thinking education* (pp. 31-49). Singapore: Springer.

Rogers, S. (2013). Using fluid power in the middle school classroom. *Technology and Engineering Teacher, 72*(6), 17.

Sahin, Y., De Pauw, J., Sukumaran, J., & De Baets, P. (2015). *Sliding friction and wear of polyoxymethylene polymer.* Gödöllő, Hungary.

Camilo A. Zorro-Mendoza *received a B.S. degree in Mechanical Engineering from Universidad Nacional de Colombia in 2018, and is finishing a B.S. in Mechatronics Engineering. He is interested in aerospace applications and designed and tested a space suit simulator presented in the Argentine Congress of Space Technology in 2017. He has built a model for estimating the concentration of CO_2 levels on a space suit's helmet. His interest in STEM education brought him to Purdue University where he developed instructional tools for teaching fluid power while integrating them with mobile applications. He can be reached at cazorrom@unal.edu.co.*



Jorge A. Leon-Quiroga *received a bachelor's degree (2015) and a master's degree (2017) in mechanical engineering from University of the Andes (Bogota, Colombia). He has research experience in CFD (Computational fluid dynamics), fluid power, and vehicle dynamics. In August 2017 he began doctoral studies at Purdue University in Dr. Jose Garcia and Dr. Brittany Newell's laboratory. Currently, his research interests are hydraulic hybrid vehicles and vehicle dynamics. He can be reached at jleonqui@purdue.edu.*

Brittany A. Newell *received a B.S. degree in Biomedical Engineering, a M.Sc. and Ph.D. in Agricultural and Biological Engineering from Purdue University. From 2013 to 2015, she worked for a contract manufacturing company in quality and regulatory engineering and as a Quality Manager. In 2015, she returned to Purdue as an assistant professor with the School of Engineering Technology. Her research interests are intelligent sensors and actuators, adaptive structures, additive manufacturing, and energy efficiency. Dr. Newell is interested in implementation of these technologies into industrial applications. She can be reached at bnewell1@purdue.edu.*

Jose M. Garcia-Bravo *received a B.S. in Mechanical Engineering from Universidad de Los Andes (Bogota, Colombia), and M.Sc. in Engineering and Ph.D. degrees from Purdue University. From 2011 to 2012, he was a research assistant professor at the Illinois Institute of Technology. Since 2015, he has been an assistant professor with the School of Engineering Technology at Purdue. His research interests include electric and hydraulic hybrid drive trains, additive manufacturing of hydraulic and pneumatic components, and energy efficiency and duty cycles of hydraulic systems. He can be reached at jmgarcia@purdue.edu.*

This is a refereed article.

Appendix 1

Code Source and Programming Logic

Control of stepper motor speed

```
...

if(Serial.available()>0){
data=Serial.read();

if(data >0&&data <=49){
int nextPosition=data;
nextPosition=map(data ,0,49,0,5000);

    if (Position <=nextPosition){
    digitalWrite (dirPin ,
    stepsPerRevolution= (nextPosition
    - Position);
    }else{
    digitalWrite(dirPin,HIGH);
    stepsPerRevolution= (Position
    - nextPosition);
  }
    ...
  }
..
```

Figure A 1. Arduino code for control of stepper motor (Bakker, 2019).

Revolution

```
...


for(int x=0;x<stepsPerRevolution;x++)
{
  digitalWrite(stepPin ,HIGH);
  delayMicroseconds (250);
  digitalWrite(stepPin ,LOW);
  delayMicroseconds (250);
          }
...
```

Figure A 2. Arduino code for stepper motor movements (Bakker, 2019).

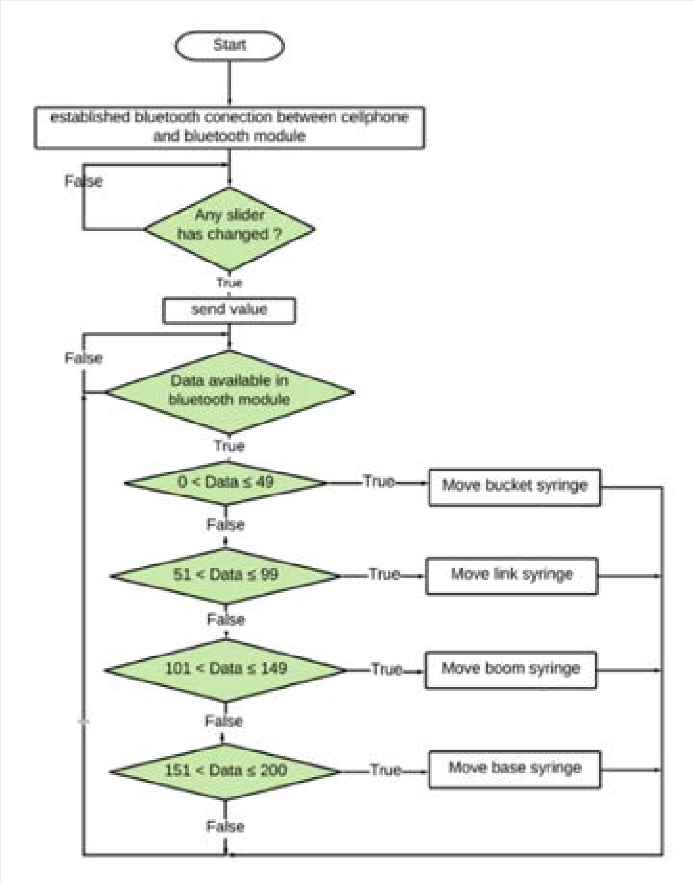


Figure A 3. Flowchart of arm control.

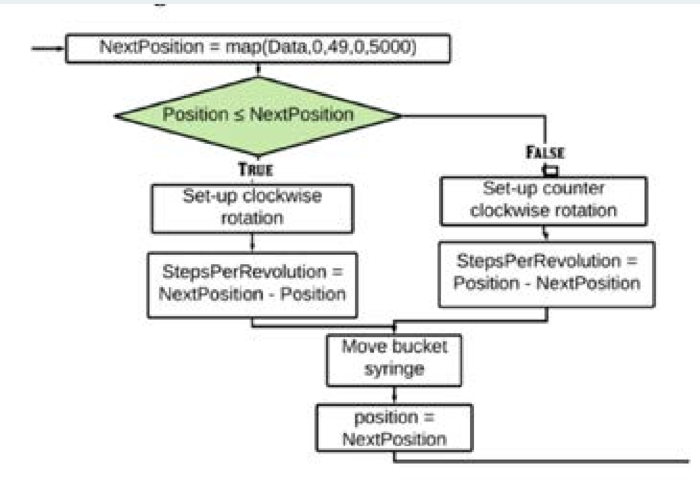


Figure A 4. Flowchart of bucket syringes movement.

Appendix 2.
Survey Questions

Presurvey Questions

- Statement 1: I understand how power is transferred in a hydraulic machine.
- Statement 2: The relationship between pressure to force is clear to me.
- Statement 3: I understand how the area of a piston affects the internal pressure of a hydraulic system.
- Statement 4: The relationship between electric current to force is clear to me.
- Statement 5: In a hydraulic excavator, the force it can lift can be increased when the area of the piston is decreased.

Post-Survey Questions

- Statement 1: The excavator arm taught me how pressure is a consequence of the load carried by the arm.
- Statement 2: This activity helped me understand how the size of the piston areas can be used to design a machine with larger load capacity.
- Statement 3: This laboratory helped me realize how flow and pressure are used to estimate the power consumed.
- Statement 4: This laboratory activity also helped me understand how hydraulic power is comparable to mechanical and electric power.
- Statement 5: With this activity I learned how current and flow can be used to produce pressure and flow in a system.

Appendix 3.
Laboratory Guide

Fluid Power Principles for an Electro-Hydraulic Arm

Objectives:

1. Recognize Pascal's principle in fluid power applications.
2. Introduce electronic tools with an Arduino platform for control of fluid power systems.

Background:

The use of electric power for propelling hydraulic and pneumatics systems is a concept that is used in many different industries and machines in the world. The use of electric power and control to move hydraulic and pneumatic machines helps increase the productivity and sustainability across various industries.

Project Goals:

1. Develop an understanding of the energy transfer mechanisms in a fluid power machine.
2. Determine forces and pressures involved in a fluid power system.

Materials:

1. One arm kit per group
2. Syringes (varying sizes)
3. Tubing
4. Multimeter
5. Stopwatch or cellphone with stopwatch
6. Mobile phone or tablet mobile device using Android OS

What to Do:

1. Take the mechanical excavator arm and test three different syringes of various sizes to raise the entire arm (5 cc, 10 cc, 20 cc).
2. Observe and take notes of the movement produced and compare between the different syringe sizes.
3. Install in one mobile phone the apk EHE 21 provided on Blackboard.
4. Take the Electro-Hydraulic Excavator and measure the Voltage and current of the stepper motor; be very careful measuring the current in the system as, if the multimeter leads are not placed correctly, an electric short will be produced.
5. Take the displacement and the time that it takes to complete a full movement of the arm.
6. With the equations below, based on the above measurements, determine the force applied and the pressure in the system.

Reflect:

Based on the above section, answer the following questions:

1. Which syringe size reached the longer distance? Do they reach the same distance? Justify your answer.
2. Which syringe size was easier to lift the arm? Justify your answer.
3. If you are required to increase the force to lift the arm with syringes of the same size, what would you propose to be done?
4. Do you think that all electrical power supply to the motor is transformed into mechanical power in the hydraulic arm? Explain your answer.
5. According to the question above and the experience in the lab, create a diagram showing the flow of energy from the electrical supply down to the syringes on the excavator demonstrator.
6. According to the experiences of the lab create a diagram showing the communication between the arm and your mobile phone.
7. What other system could be used to push the syringes?
   - Equations. Assume 100% efficiency.

$$P_{electrical}=V*I \qquad P_{mechanical}=F*v \qquad p=F/A$$

Appendix 4.

Bill of Materials for EHE 2.2

Table A1. EHE Bill of Materials

MATERIAL/COMPONENT	VENDOR	NUMBER PART	QUANTITY	UNIT PRICE US$	TOTAL EXPENSES US$
HC-06 SLAVE BLUETOOTH SERIAL PORT	Amazon	8541545644	1	7.99	7.99
112PCS 2.54MM MALE AND FEMALE PIN HEADER KIT	Amazon	B07CWSXY7P	1	13.99	13.99
ANTI-BACKLASH NUT BLOCK	Amazon	824007544745	2	9.99	19.98
USONGSHINE NEMA 17 - MOTOR PASO A PASO	Amazon	4401288985502	4	9.99	39.96
SET LEAD SCREW, COPPER NUT, COUPLER, PILLOW BEARING BLOCK	Amazon	LXMY1490	4	12.99	51.96
HATCHBOX PLA 3D PRINTER FILAMENT	Amazon	849344024248	1	22.99	22.99
6800MAH DC 12V SUPER POWER RECHARGEABLE	Amazon	B074PQK4CC	1	19.88	19.88
ARDUINO MEGA 2560 REV3	Arduino	7630049200067	1	40.3	40.3
CAPACITOR 100UF 25V RADIAL	Digikey	493-16164-1-ND	1	0.33	0.33
SWITCH ROCKER SPST 6A 125V	Digikey	CH865-ND	1	1.2	1.2
CONN PWR JACK 2X5.5MM SOLDER	Digikey	CP-002A-ND	1	0.6	0.6
RESISTOR 100 OHM 1/4W 5% AXIAL	Digikey	CF14JT100RCT-ND	4	0.1	0.4
3/4″ X 1/2″ CORNER BRACE	Grainger	31162503	4	0.67	2.68
COMPOSITE WOOD SHELF WITH SQUARE CORNERS, 12″ DEEP X 24″ WIDE	McMaster	50385T9	1	8.19	8.19
PAN HEAD PHILLIPS SCREW M3 X 0.5 MM X 5 MM	McMaster	92000A114	1	4.52	4.52
PAN HEAD PHILLIPS SCREW M3 X 0.5 MM X 30 MM	McMaster	92000A132	1	7.77	7.77
PAN HEAD PHILLIPS SCREW M5 X 0.8 MM X 25 MM	McMaster	92000A330	1	10.19	10.19
PAN HEAD PHILLIPS SCREW M5 X 0.8 MM X 30 MM	McMaster	92000A332	1	6.83	6.83
HEX NUT M3X0.5	McMaster	90591A121	1	1.57	1.57
HEX NUT M5X0.8	McMaster	90695A037	1	3.13	3.13
PHILLIPS ROUNDED HEAD SCREWS 10-32 THREAD SIZE, 7/8″	McMaster	90272A832	1	6.41	6.41
PHILLIPS ROUNDED HEAD SCREWS 10-32 THREAD SIZE, 3/4″	McMaster	90272A831	1	6.05	6.05
PHILLIPS ROUNDED HEAD SCREWS 10-32 THREAD SIZE, 3/8″	McMaster	90272A827	1	4.07	4.07
PHILLIPS ROUNDED HEAD SCREWS 10-32 THREAD SIZE,1-1/4 ″	McMaster	90272A835	1	7.51	7.51
PHILLIPS ROUNDED HEAD SCREWS 8-32 THREAD SIZE, 1/2″	McMaster	91735A194	1	5.82	5.82
PHILLIPS ROUNDED HEAD SCREWS 12-24 THREAD SIZE, 5/8″	McMaster	90272A609	1	8.9	8.9
WASHER NO.10	McMaster	90107A011	1	3.64	3.64
HEX NUT 8-32 THREAD SIZE	McMaster	91240A009	1	3.65	3.65
WING NUT 10-32	McMaster	92001A311	1	6.46	6.46
HEX NUT 10-32	McMaster	91841A195	1	3.77	3.77
BINDING BARRELS AND SCREWS 8-32 THREAD SIZE, FOR 2-1/2″	McMaster	93121A370	1	10.69	10.69
UNTHREADED SPACER 3/8″ OD, 1/2″ LONG	McMaster	90147A130	1	5.84	5.84
UNTHREADED SPACER 3/8″ OD, 5/8″ LONG	McMaster	90147A140	3	5.9	17.7
UNTHREADED SPACER 3/8″ OD, 2″ LONG	McMaster	90147A220	3	6.43	19.29
PLASTIC SYRINGE 10 ML	McMaster	7510A653	1	7.5	7.5
DECORATIVE FINISHING NAILS BRASS, 1″ LONG, 18 GAUGE	McMaster	97936A109	1	2.89	2.89
6061 ALUMINUM WITH CERTIFICATION 3/16″ DIAMETER, 6 FT	McMaster	1615T12	1	15.63	15.63

CLEAR CAST ACRYLIC SHEET 24″ X 36″ X 1/8″	McMaster	8560K261	1	35.24	35.24
CLEAR CAST ACRYLIC SHEET 12″ X 24″ X 1/8″	McMaster	8560K257	1	16.7	16.7
VELCRO® BRAND 4″ X 2″ EXTREME TAPE FASTENER STRIPS	Menards	2753165	5	3.79	18.95
PCB SINGLE LAYER OSHPARK	Oshpark	N.A.	1	19.95	19.95
POLOLU 9V, 500MA STEP-DOWN VOLTAGE REGULATOR D24V5F9	Pololu	2845	1	4.95	4.95
DRV8825 STEPPER MOTOR DRIVER CARRIER, HIGH CURRENT	Pololu	2982	4	10.45	41.8
DC BARREL PLUG TO 2-PIN TERMINAL BLOCK ADAPTER	Pololu	2448	2	1.95	3.9
				Total cost	**541.77**