Design of a Transparent Hydraulic Educational Demonstrator Utilizing Electrically Controlled Valves

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Abstract-- **This Innovative Practice Full Paper presents the development of a hydraulic demonstrator used to illustrate simple mechanical and electrical concepts to high school and undergraduate students. The system utilizes a remote controller which communicates with a microcontroller, used to open and close electrically controlled valves allowing fluid to transfer, extending and retracting hydraulic cylinders. Once actuated, each hydraulic cylinder will rotate individual components of the mechanical arm to mimic the motion of typical industry standard excavating equipment. This arm is composed of a unique multi-layered Lexan design permitting the system to be transparent. One major advantage of this transparent design is having a demonstrator which allows students to easily observe fluid power systems, their functions, and the mechanics of the arm. The arm is assembled using quick disconnect pins making the mechanical arm easy to assemble and disassemble for storage and portability purposes. This allows the arm to be used in a wide range of learning settings, including outreach opportunities, recruiting events, and classrooms, where it can be used to teach multiple concepts using a variety of different laboratory experiments. The courses that would benefit from this demonstrator range from, but are not limited to, fundamental engineering courses such as statics and dynamics or advanced courses such as fluid power and data acquisition courses.**

I. Introduction

Digital hydraulic is a promising field in the fluid power industry. Digital hydraulics combines electronics with traditional fluid power systems creating intelligent fluid power systems. Today, most engineering systems have integrated electronics, so it is important to have students learn and interact with these systems early in their education. While digital hydraulics has brought many advancements to fluid power systems, there are limited tools used to teach these systems in education. Students need to understand, not only, mechanical equations to analyze a system, but also how integrated systems work and interact with each other. A major problem with obtaining demonstrational tools is that many of them are relatively expensive or often require expensive tools to assemble and build them. These demonstrational tools are often only introduced in engineering education later in students' coursework, causing students in the earlier stages of their education to lose interest and focus in their field.

A study conducted on an introductory Information Systems course at Devry University reported that the introduction of a Raspberry Pi into the students' coursework increased the overall satisfaction of the course by 11% [1]. Students in all areas of education exhibit various levels of motivation, many students seem to be more attentive to types of learning such as hands on learning and teamwork projects. It is the duty of the professor to understand their most effective way of teaching to further the students education [2]. An effective method of teaching is using a demonstrational tool that allows students to effectively visualize concepts taught in the classroom, as well as, concepts related to the book, keeping the classroom from the traditional approach of teaching. The traditional approach being, the professor lectures and assigns readings and problems while the students listen, take notes, and solve problems individually [3]. This teaching system is inefficient to cater to the needs of the technological advancements of the 21st century. Engineering tools and demonstrators shown to students earlier in their education allow students to experience multiple fields of engineering. This experience introduces the diversity of engineering fields and helps to positively influence students development and retention [4].

The objective of this project is to build a hydraulic educational demonstrator, which utilizes electrically controlled valves to introduce students to fluid power systems with integrated electronics. Such a tool would also be useful in teaching open source microcontroller courses, where students can learn fundamentals about microcontrollers that they may encounter in engineering projects; including automotive applications, where students can learn how computers work in current automobiles [5]. While this tool's focus would be on hydraulics and microcontroller education, it would also be used in a magnitude of other courses including: Electric Circuits, Statics, Dynamics, Data Acquisition, etc. taught in university and high school education, but could also be used as a recruitment tool to interest K-12 grade students into STEM fields.

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II. Background

In 2009, Purdue University designed and created a micro-excavator arm which was demonstrated to students in K-12 grade classes. This gave students the opportunity to work in a team, with the purpose to create and design a tool that could teach other students concepts in statics and mathematics [6]. Many of the tools being used in education are currently opaque and restrict the observer to have a full view of the tool. In 2017, the University of Southern Indiana designed a miniature hydraulic demonstrator that utilized a layered Lexan design to address this problem [7]. Lexan is a transparent polycarbonate that is flexible, yet tough. This material has been used in engineering to create items such as kitchenware, DVD's, headlamps, etc. Lexan is relatively cheap and can be purchased in large sheets. This makes it a suitable candidate for group projects where students can cut out, machine, and assemble simple shapes, to bolt them together and build educational tools; giving them experience designing and building equipment. This was one major quality of this unique demonstrator.

Building and designing such an educational tool benefits multiple groups of students. The first group of students that benefit from the project are those who design build and construct the demonstrator, second being students who learn from the demonstrator in their coursework and third being students who participate in University Science Fairs and University Outreach Programs [8]. Currently the first iteration of the arm, which utilizes mechanical controlled valves rather than electrically controlled valves, has been used in multiple events to promote STEM fields and university programs at The Indiana Pacers STEM Fest and University Science fairs. There have been many tools over the years to introduce and teach concepts to students, yet there are very few tools used to support engineering education today.

III. Design

The excavator was designed to meet parameters discovered based off user feedback from the first prototype, which utilized mechanical valves to actuate hydraulic cylinders on the excavator [9]. The feedback from previous users indicated that the system needed to be smaller and more portable. Figure I, shows the final design of the miniature excavator arm that operates using a pump, four electronic valves, a microcontroller, four mechanical actuators, and eight variable flow control valves.

Figure I
Mechanical Excavator Design

Figure II, depicts the breakdown of the miniature excavator into three major systems, including a mechanical, a hydraulic, and an electrical system. The electrical system breaks down into four major components; the electric pump, the microcontroller, data acquisition sensors, and the remote controller. The fluid system consists of a water reservoir, valves, hydraulic cylinders and variable flow control valves. The mechanical system is broken down into 4 components of the arm; a rotating base, a boom arm, a dipper arm, and a bucket.

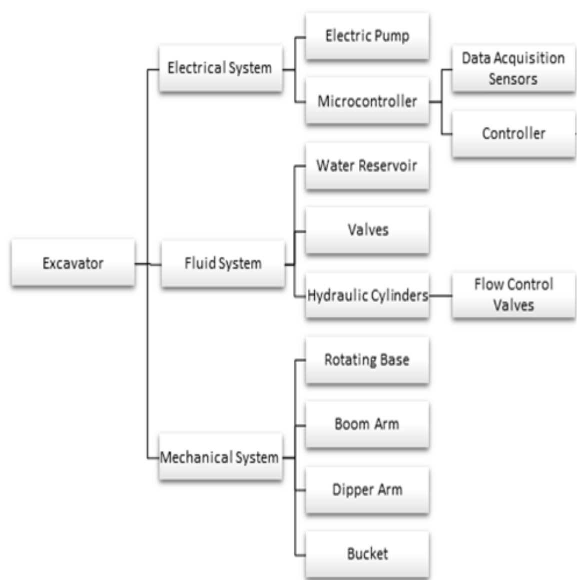

Figure II
Subsystem Breakdown

IV. Mechanical System

The excavator is built from a unique layered Lexan design which allows the excavator to be hollow in the center [7]. The hollow center removes a large portion of weight from each section of the arm. This hollow layered design is achieved by bolting different shapes of Lexan that were cut out and bolted together using multiple layers of ⅜" Lexan shown in Figure III and Figure IV.

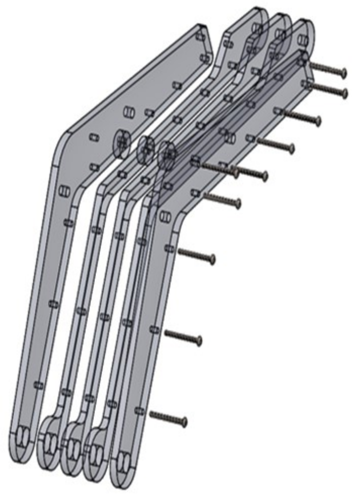

Figure III
Exploded View of Boom Arm

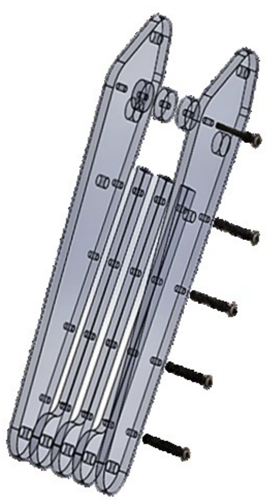

Figure IV
Exploded View of Dipper Arm

The hollow design also allows the hydraulic actuators to be mounted in the arm and seen through the side of the excavator making it safe to observe during operation, seen in Figure V.

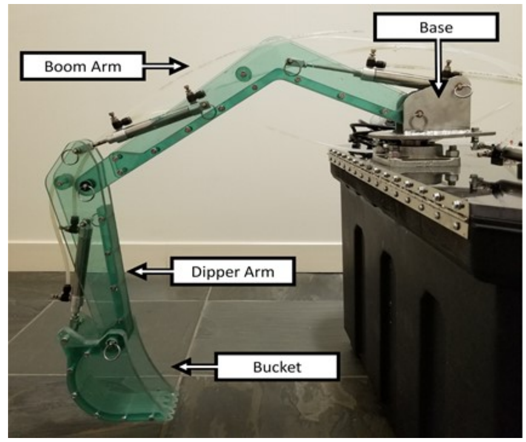

Figure V
Mechanical Arm

V. Hydraulic System

Four electronically controlled valves are used to transfer fluid to each of the four hydraulic cylinders. These cylinders are used to move and rotate the mechanical arm. Flow control valves are attached to the inlet and outlet of each actuator to regulate the speed that the cylinders extend and retract. These valves utilize a variable needle valve which controls the flow through each of the valves. This configuration, known as a meter-out circuit, provides the opportunity to teach different fluid power configurations and their purposes to students. The implementation of these variable flow control valves is depicted in Figure VI. The control valve at the inlet (on the left), controls the retraction of the actuator; while, the control valve at the exit (on the right), controls the extension of the actuator.

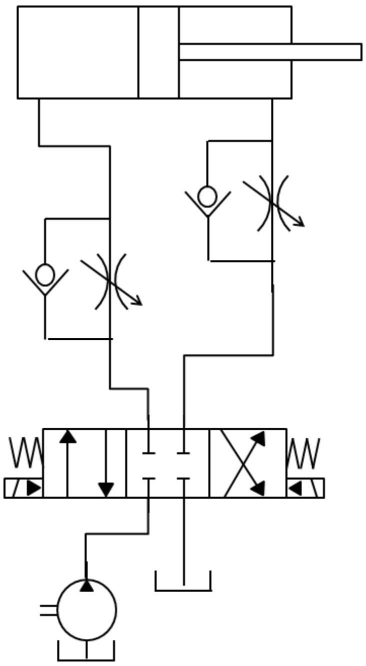

Figure VI
Hydraulic Circuit

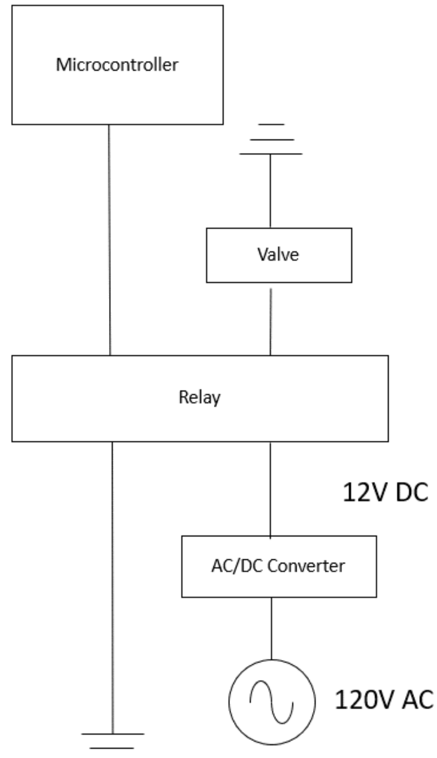

Figure VII
Electric Circuit

VI. Electrical System

This excavator utilizes an electro-hydraulic system actuated using a microcontroller, seen in Figure VII. Once a button is pressed on the remote, a signal is sent to an Arduino microcontroller, shown at the top of the figure, which actuates the relays that hold the electric load. These relays are used to the load off the microcontroller. Once actuated, the relays connect the circuit to the electronic valves and send 12V to the valve, opening the valve. The electronic valve contains a spring return for when the button is released causing it to move back to its closed center position. A wall outlet will be used to power the electronic valves, but the power will be stepped down to 12V using a converter to make the excavator safer for students to use.

VII. Budget

The complete budget necessary to build the transparent hydraulic demonstrator is $1,478. An overview of the components required is shown in Table I, along with the pricing. To keep the demonstrator available for teaching, all components were found commercially available for purchase. The tools required to cut out and assemble the demonstrator are common hand tools that are relatively inexpensive, and the demonstrator does not require any heavy machinery to construct. The most expensive parts to build the miniature excavator come from the electronic valves costing about $304.

Table I
Cost of Excavator Components

Item	**Cost (USD)**
Tubing and Fittings	$187
Portable Tool Chest	$100
Cylinders	$112
Micro-controller, Relays, Sensors	$180
Electronic Valves	$304
Water Pump	$125
Rod Clevis, Bearings, etc.	$235
Gauge and Manifolds	$35
Base Materials	$200
Total Cost	$1,478

VIII. Educational Opportunities

One of the main functions of the miniature excavator arm was to be utilized in different engineering classes. Electrical components demonstrated to students would be electronic control valves and microcontrollers and how they communicate through electronic signals. Such a project is advantageous in teaching students' effective communication skills with other team members and teams, as well as, concepts of electro-hydraulic circuits and various electric components. Students are lacking in projects that focus on communication and teamwork to overcome problems. The addition of electronic valves to the excavator arm was to create additional areas of education where the excavator could be used. The original mechanical excavator only extended to areas of statics, mechanical emphasis dynamics, dynamics of machinery, fluids, and fluid power; while, the new design incorporates electric circuits to make the excavator more versatile in engineering courses. A few examples of how the miniature excavator is incorporated into engineering courses are shown below:

Statics course examples:
- Calculating the force at connecting arm joints
- Tipping example in Statics
- Calculating force exerted by cylinders

Fluid power course examples:
- Functions of fluid power operations
- Understanding and designing fluid power circuit schematics
- Component sizing

Circuits course examples:
- Understanding electric circuits and their implementations
- How a microcontroller communicates with a circuit

Data acquisition examples:
- Acquire data
- Sensor calibration

IX. Workshops

Workshops and other public STEM Field events are an ideal way to interest students to get involved in projects. The miniature excavator arm was also built to help immerse students in an active hands-on learning environment. Tools and projects like this one are effective ways to teach students the importance of teamwork and utilizing each other's strengths to complete a task [10]. To involve this technological tool, a workshop would need to consist of students with little to no prior knowledge of hydraulics or electric circuits. The person demonstrating the excavator would give students a background on these subjects. Giving the students an insight to how these tools are used in industry and how they operate together. The background that could be taught on hydraulics consist of 1) the components that operate hydraulics such as valves and cylinders, 2) different pressures that hydraulics operates at, whether a fluid could be considered compressible or not, 3) understanding hydraulic circuits, 4) optimization of the system by implementing a meter-out system. The electric component and electric circuit background would consist of 1) understanding simple electric circuits and their schematic drawings, 2) how computer programming communicates with electrical components, 3) understanding the difference between an inverter and converter, as well as, the purpose of a relay. Students attending a workshop would be grouped into teams and given the task to construct the excavator arm given the necessary components. After the event, a survey for the students would be given asking; what they learned during the workshop, how could this workshop be improved, including future workshops and events involving this project or projects like it.

X. Conclusion

This hydraulic demonstrator utilizes electronically controlled valves, data acquisition sensors and a microcontroller to teach fundamental engineering concepts in early engineering education. A layered Lexan design was utilized allowing students to observe the arm from multiple angles during demonstration in the classroom. Its focus is to teach hydraulic systems, microcomputers and data acquisition, while also providing a tool that can be used in many of fundamental engineering courses to enhance the learning experience for students in high school or undergraduate programs. Its portability allows it to be used in multiple different classes, events, and workshops and can be operated using a standard 120 V AC / 15 A electrical outlet. The total cost of the electrically controlled demonstrator is $1,478.

Acknowledgements
This project was funded by the Barnett Award provided by the University of Southern Indiana

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