Laboratory Activities of the Fundamentals of Mechatronics Course for Undergraduate Engineering Technology Students

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Abstract

A mechatronics course was developed as a multidisciplinary course for undergraduate students in Mechanical Engineering Technology (MET) and Electrical Engineering Technology (EET) at Oklahoma State University. The Fundamentals of Mechatronics course serves as the foundational course for three other Mechatronics courses, which will be the core of the proposed minor and graduate programs at the Division of Engineering Technology. It is a three credit hour course with two-hour lecture and one-hour laboratory session. It is currently an elective course but will be a required core course for the mechatronics minor. This paper presents the development of laboratory activities for the course. The laboratory activities focus on a wide variety of electrical, mechanical, and control applications synchronized with the lectures. The labs start with designing a linear regulated power supply to enhance the electrical background of students. The experiments extensively use National Instrument's LabVIEW graphical programming language and myRIO hardware to control electro-pneumatic systems and dc motors along with various other sensors interface. The paper presents the development of the laboratory infrastructures and the challenges faced during the development of this interdisciplinary course. One of the major challenges stemmed from the fact that the class was comprised of two groups of students, MET and EET, who have much different backgrounds. Sample course material, laboratory activities, student assignments are presented to show the pedagogical approach followed in the course. Assessment of student performance and feedback from students are also presented. The paper will be helpful for instructors who are looking for developing a mechatronics laboratory for students with a diverse background latter.

Introduction

Mechatronics education [1–3], to develop a multi-disciplinary workforce for the recent technological advancements [4], [5] and meet the industry 4.0 standard [6], is drawing increasing attention of educators in four-years degree programs [7]. With this respect, mechatronics programs are offered both at undergraduate [8–13] and graduate [14], [15] levels by a number of universities. The history of mechatronics dates back to early 1970s, when the term *mechatronics* originated by Tetsuro Mori, an engineer of Yasakawa Electric Corporation in Japan [16]. Initially the term mechatronics was dedicated for systems which are combinations of electrical and mechanical components, in general referred as electro-mechanical systems. With the revolution in semiconductor, computer, and control system technologies, these disciplines are included in the paradigm of mechatronics.

Currently, the term mechatronics is ubiquitous and is popular in almost all engineering disciplines. Often times mechatronics is used for applications, such as industrial automation and robotics [17], automotive engineering, machine vision, expert systems, etc. Most of the cases, mechatronics education [1–3] is often tied up with robotics [18] and the undergraduate and

graduate programs are named as mechatronics and robotics. The mechatronics engineering curriculum at universities, therefore, differs from each other [11], [19–21] and tailored as per the programs' focus areas. For instance, some of the universities have programs that focus on robotics while others focus on mechatronics in manufacturing, production or industrial automation. The robotics program is further subdivided into disciplines, such as industrial robotics, mobile robotics, and medical robotics. At some universities the curriculum is also considered as micro-controller education [22].

The Division of Engineering Technology at Oklahoma State University is planning to offer a graduate program in mechatronics and robotics. In the process of the developing the master's program, the division offered its first elective course on mechatronics in spring 2017. To further support this effort, a new minor in mechatronics will be offered starting fall 2019. The minor will be for both mechanical engineering technology (MET) and electrical engineering technology (EET) students in the division. MET students are required to complete twenty-one credit hours, whereas for EET students it is sixteen hours. The objective of the minor is to train MET(EET) students with required expertise in EET (MET) courses. Both MET and EET minor students will undergo two specialized mechatronics courses, namely Fundamentals of Mechatronics and Mechatronics System Design that will educate them with the integrated mechatronics design concept.

The Fundamentals of Mechatronics course is an introductory course for introducing students with basic mechatronic systems and components, such as electrical and electronic components, sensors and actuators and their interfacing with micro-controllers. This three-credit-hour course, which includes one-credit-hour of laboratory component, is an elective course. The course is different from the required Basic Instrumentation and Data Acquisition course offed by the MET and EET program, respectively. This course focuses on interfacing of the sensors and actuators with micro-controllers, electrical wiring and programming with fundamental understanding of sensors and actuators.

A number of different approaches are suggested in the literature for the mechatronics course, e.g., project-based approach [9] and competition based approach [10], to name a few. Keeping in mind the diverse background of students enrolling in the course, i.e., EET and MET, and basic knowledge of electric circuits as the prerequisite, the course reviews fundamental analog and digital circuits to bring the students to a level where they can learn programming concepts. To emphasize on the hands-on experience, the course uses a hybrid approach of teaching and evaluation. The lecture portion of the course is evaluated based on homework assignments and midterm examinations, and the hands-on laboratory portion of learning is evaluated based on final design project. The uniqueness of this course, when compared with other mechatronics courses, is the industry-oriented pedagogical approach for technology students, which combines the extensive hands-on activities and student-centered pedagogy. Students are motivated with real-world industrial applications to actively participate in the course both during the laboratory and lecture sessions. The second feature of the course is that it uses only basic electrical circuits as a pre-requisite, opening up opportunities for a larger pool of mechanical students to opt for the course.

The course is designed with the following learning objectives:
- Provide students an overview of mechatronic systems and their applications.
- Provide students instructions on various mechatronics systems, sensors, actuators and their applications to engineering problems.
- Provide students hands-on experience on identification and usages of electrical and electronic components and test equipment.
- Provide students hands-on experience on signal conditioning circuits such as amplifiers, D/A and A/D converters, sensors and actuators.
- Provide students hands-on experience for interfacing sensors and actuators for data acquisition and control using NI LabVIEW and myRIO hardware.

The remaining sections present the pedagogical approach, course content, laboratory development, sample laboratory exercises, and course evaluations.

Pedagogical Approach of the Course

This course uses a "learning-center pedagogy" for teaching the class. The lecture focuses on explaining the fundamental concepts of the subject matter while seeking active participation from the students. Active learning approaches are used during the lecture sessions, which build upon the students' prior knowledge of the subject matter discussed during the class and the requirement to imbibe the concepts. The course content is listed in the Table 1 below. The lecture and laboratory use chalkboard, PowerPoint presentations, animation and videos. The course often seeks interim feedback from the students to revise the topic as per the students' requirement. Homework assignments, midterm exams, and final project serve as feedback for the course.

Table 1: Fundamentals of mechatronics course content

Sl. No.	Topic
1	Review of electrical and electronic components
2	Regulated power supply and transistor based drive circuits
3	Digital electronics and introduction to micro-controller
4	Signal conditioning and data acquisition
5	Analog sensors (position, distance, temperature, etc.)
6	Digital sensors (proximity sensors and encoder)
7	Actuators (dc motor, stepper motor, servo motor)

The laboratory activities of the course start from the first week of the semester. Before starting the laboratory activities, the students are required to take the laboratory safety quiz. The first lab introduces electric circuit simulation using NI Multisim circuit design software. The software is used throughout the semester for testing and validating the electric and electronic circuits used during the course. The introduction of this software helped the diverse background students from EET and MET programs to visualize the electric circuit concepts. This found to be a very effective tool to teach MET students complex analog electronic circuits used to design the power supplies and driver circuits for solenoids and DC motors.

Moreover, learning the subject of mechatronics requires certain level of programming skills as prerequisite. Therefore, the selection of microprocessor for controlling the mechatronics devices become crucial part of the course development. The selection of controller platforms are different depending on universities and mostly determined by expertise and preference of the instructor. In the hindsight of diverse background of MET and EET students, LabVIEW is selected as the programming language for the course.

The primary reason for selecting LabVIEW as the programming language is its graphical nature. Since knowledge of programming language is not a course prerequisite, the graphical programming makes it easier to grasp the concept very quickly. It is observed that after eight hours of review and hands-on practice, student with no prior knowledge in LabVIEW could begin writing programs with a fair level of understanding. NI myRIO, which is native to LabVIEW, is used as the micro-controller for the course and all the features can be programmed using LabVIEW. Another reason of selecting LabVIEW is the availability of license, provided by the university, and the abundance of resources such as videos and example projects. Students are suggested to watch the videos to strengthen their understanding. In the next section, the laboratory development and sample lab activities are presented.

Laboratory Development and Sample Laboratory Activities

Since the Fundamental of Mechatronics course is offered for the first time in the division, it was necessary to develop a completely new laboratory. The MET program in the division has a well established fluid power laboratory with multiple hydraulic and pneumatic trainer kits. Therefore, it was decided to use the existing facilities as the application areas to mimic various pneumatic and hydraulic machinery. Selection of controller was the next challenging job. There were multiple options available in the market, such as Arduino, PIC micro-controller, MSP 432, AB PLC, and NI myRIO. Both the AB CompactLogix PLC and NI myRIO found to be very suitable for students with minimum or no experience in programming. All the laboratory equipment along with sensors, actuators and driving circuitry were procured. A sample list of sensors, actuators and drivers used for the laboratory is given in the Table 2 below.

Table 2: List of sensors and actuators used for the laboratory activities

Sl. No.	Sensors/Actuators
1	Push buttons
2	Light emitting diodes
3	IR distance senor
4	DC motor with encoder
5	Bipolar stepper motor
6	Servo motors
7	H-bridge drivers for DC and stepper motors
8	Relay board
9	Pneumatic cylinder and direction control valves

The laboratory activities are designed to corroborate the lectures. Students use LabVIEW myRIO and Multisim software package, provided by the university. Following the college-wide policies,

students are required to use their personal laptops for the labs. Additional desktop computers are also provided as a backup. A myRIO is issued to each student for working on homework assignments and pre- and post-laboratory activities outside the class. Some of the sample laboratory experiments are briefly appended below.

Lab #1 Introduction to NI Multisim and design of variable regulated power supply

Power supply is the workhorse of any mechatronic system. In the first laboratory exercise, which spans over two sessions, NI Multisim simulation software is reviewed with examples of electric circuit design and simulation.

Students use the software to design the linear regulated variable power supply, shown in Figure 1, and simulate the output. Upon visualizing the function and operation of the circuit, hands-on exercise is performed to build the power supply on a breadboard.

There are three objectives of the lab: 1) study the application of diode and voltage regulator IC, 2) learn circuit simulation technique before building any hardware, and 3) become familiar with standard test equipment, electrical and electronic components, such as multi-meter, function generator, DC power supply, oscilloscope, rectifier diodes, potentiometer, voltage regulator IC, and safety procedure to perform

Figure 1: DC regulated power supply using full wave bridge rectifier and LM317 adjustable voltage regulator.

experiments. It is often observed that the students use the power supply circuit for their final class project.

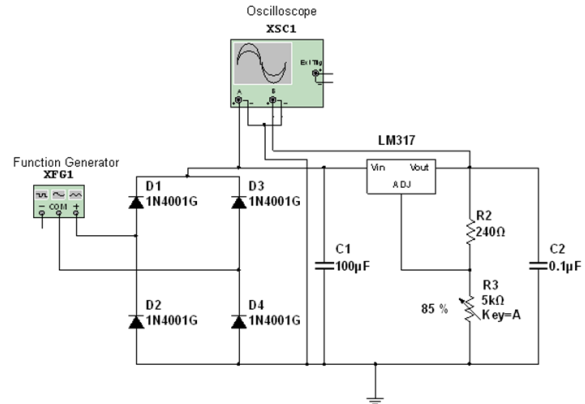*Lab #2 Introduction to LabVIEW programming and structures*

The second lab exercise introduces students with the fundamental concepts of LabVIEW. This spans over four laboratory sessions; a total of eight hours. During these four laboratory sessions, students are provided with hands-on practice on the LabVIEW environment. Every session focuses on multiple concepts of the graphical programming language. The goal is to provide students with certain level of programming experience for the future mechatronics in-class and laboratory activities. These practice sessions also help students to opt for NI's certification programs, i.e., Certified LabVIEW Associate Developer (CLAD) examination.

In the first lab session, students are familiarized with the concept of virtual instrument (VI) and use of front panel and block diagram structure of the LabVIEW graphical programming language. A review of the control and function pallet with associated controls, indicators, nodes and functions is carried out. The main focus of this session is to understand the data flow concept of LabVIEW and use numeric, Boolean,
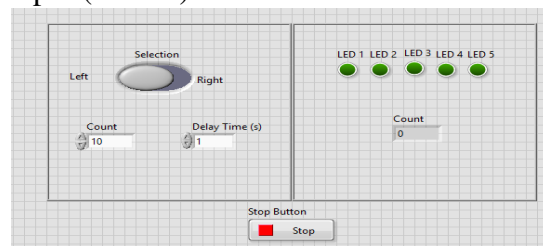

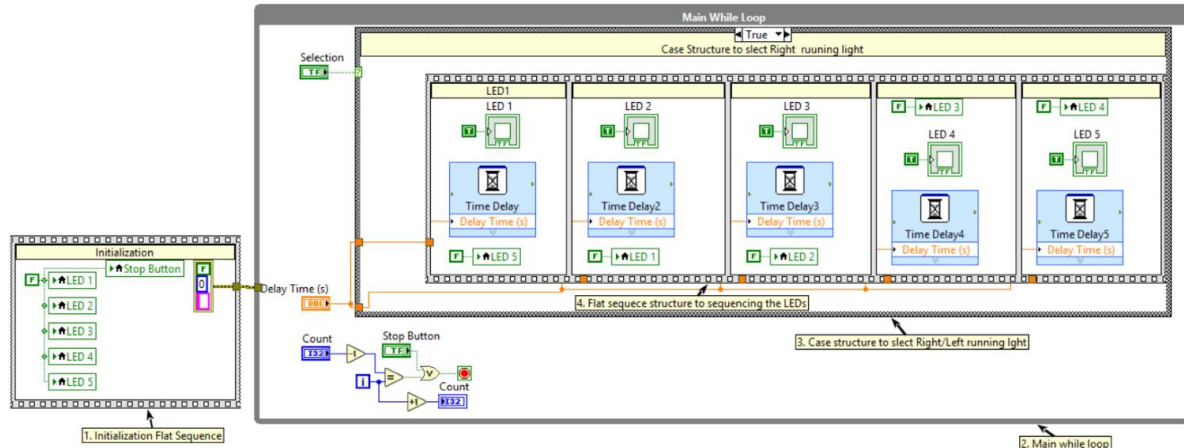Figure 2 (a): Front panel for running LED light.

Figure 2 (b): LabVIEW block diagram for running LED lights.

and comparison function pallets to write and execute mathematical expressions. Students are assigned with multiple home work assignments as practice. They are also advised to watch videos provided by NI to expedite the learning process.

The next lab session continues the review of the concepts on data types and various structures. Functioning of while loop, for loop, case structure, and timing functions are practiced during the lab session with practical examples, such as up and down counter, running LED lights, traffic lights. In the third session, the students are introduced to the complex data types such as arrays, clusters, strings and various functions/nodes available for manipulating these data for specific purpose.

To improve the programming skills, in the fourth week, the students are assigned a practice example which combines all the previously taught concepts. The front panel and block diagram of a sample example program is shown in Figure 2 (a) and (b), respectively, where the objective is to use while-loop, case structure, sequence structure, and various controls and indicators to design a running light, which can run from left to right and vice versa for a given number of times. It is observed that with the eight hours of training on LabVIEW, the students gained a desired level of expertise for writing codes by themselves.

Lab #3 Introduction to myRIO and digital input and output

NI myRIO, shown in Figure 3 (a), is a student version of the NI CompactRIO hardware for monitoring and control applications. It provides a powerful architecture with a Xilinx Zynq-7010, all-programmable system on a chip, on board which integrates dual-core ARM Cortex-A9 processor and an Artix-7 FPGA seamlessly. There are four components of the myRIO, which makes it a good choice for mechatronics applications: 1) a real-time processor, 2) a user-programmable FPGA, 3) modular I/O, and 4) a complete software tool chain for programming. The NI myRIO-1900 provides four single ended and two differential analog inputs (AI), multiplexed to a single analog-to-digital (ADC) converter , six analog output (AO) with dedicated digital-to-analog (DAC) converters, and 40 digital input and output (DIO) along with audio and power output in a compact embedded device. The NI myRIO-1900 has both USB and wireless 802.11b.g.n connectivity to connect it directly to the host computer and network,
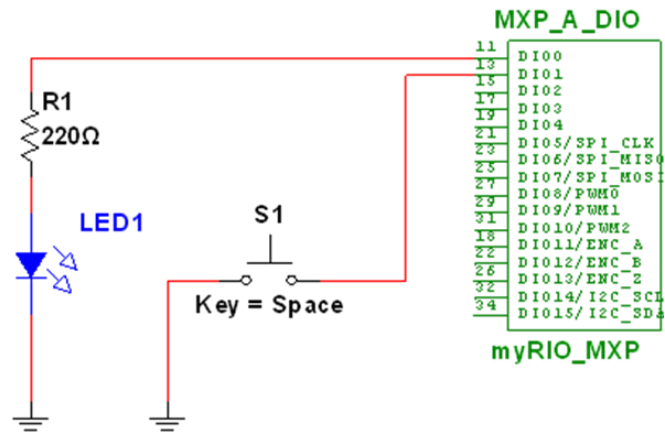
Figure 3 (a): Inputs and outputs connection of NI myRIO.

Figure 3(b): Connection diagram of digital input and output interface circuit.

respectively. The Figure 3 (a) shows various inputs and outputs of myRIO-1900.
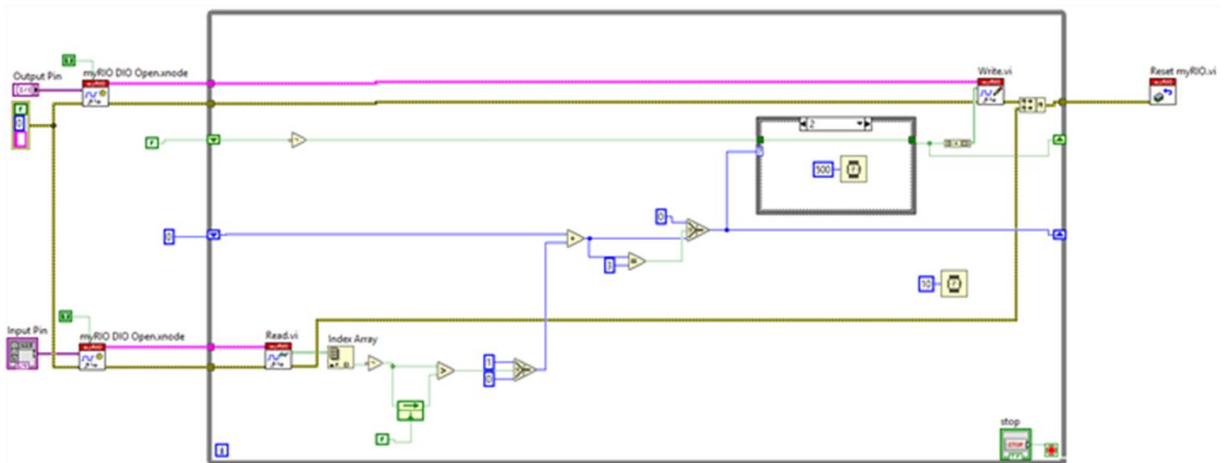

Figure 3(c): LabVIEW block diagram for digital input and output interfacing.

In this laboratory exercise, the myRIO architecture and LabVIEW tool kit are introduced. Programming myRIO requires an understanding of advanced LabVIEW skills, i.e., LabVIEW real-time. In the first part of the lab the students set up the myRIO, update the firmware, and test the on-board accelerometer sensor for the proper functioning of the device and associated LabVIEW real-time software. The second part introduces students to create a myRIO project using LabVIEW and interfacing digital inputs and outputs. As a simple case study, a push button is used as input and light emitting diode (LED) as output in the exercise. The hardware connection diagram is shown in Figure 3 (b). The interface and control programming, as shown in Figure 3 (c), is divided into three steps:

- Lighting up the LED with one push of the button,
- Blinking the LED with one push of the button, and

- Repeating the sequence of lighting up the LED with first push, blink with second push, and turning off with third push.

The interactive visual exercise motivates students to learn more about the graphical programming language. It also emphasizes on the concept that, with same hardware connection, multiple functions can be programmed on to the device, which is the primary advantage of controlling systems using micro-controllers.

Lab #4 Analog sensor interface with myRIO and distance measurement

The main objective of this laboratory exercise is to learn analog sensors and their interfacing with myRIO. The exercise uses an analog infrared (IR) range sensor, which is programmed to use both as a proximity switch and distance measuring sensor.

The lab introduces students with the operation principle of the IR sensor and its connection with myRIO. During the laboratory exercise, the students are engaged in writing the LabVIEW program for opening the corresponding analog channel based on the hardware connection and read the analog voltage from the sensor. Further, the acquired voltage reading is converted to distance by calibrating the sensor. The proximity sensing function is observed by blinking an LED when the object appears at certain distance.
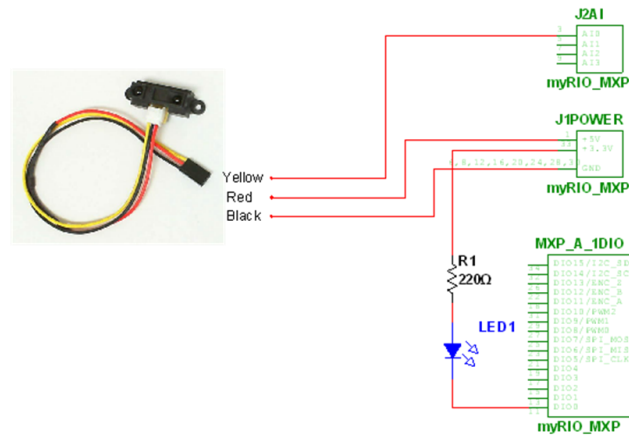
The electrical connection diagram and the block diagram are shown in Figure 4 (a) and (b), respectively. As a post-lab assignment the students are asked to modify the code for different applications. The ease in programming using LabVIEW provided took kits, visualize the data flow, and debug the code with no programming background created strong learning interest among students.

Figure 4 (a): Connection diagram of IR sensor interface and digital output.
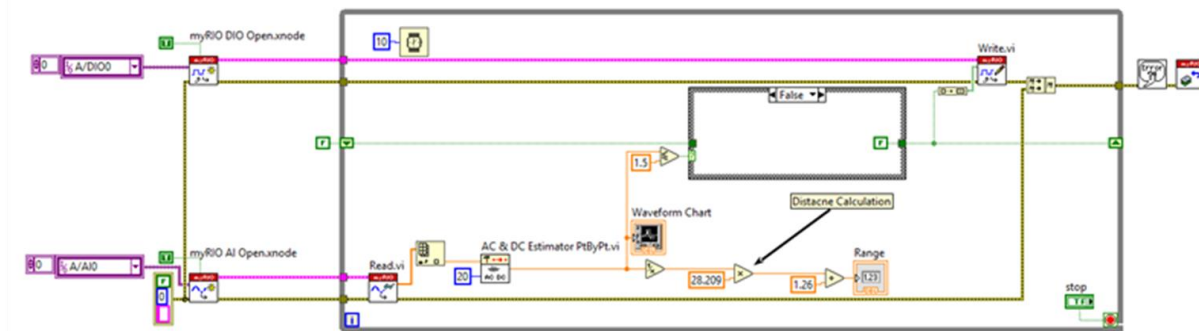

Figure 4 (b): LabVIEW block diagram for interfacing IR range sensor, blinking LED with proximity and measuring distance.

Lab #5 Sequencing operation of pneumatic cylinders using myRIO and trainer kit
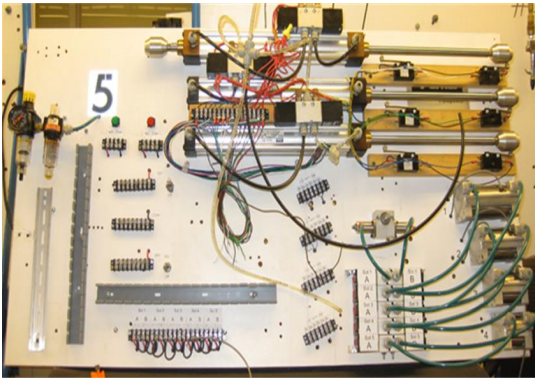

Figure 5 (a): Pneumatic trainer kit in the fluid power lab.
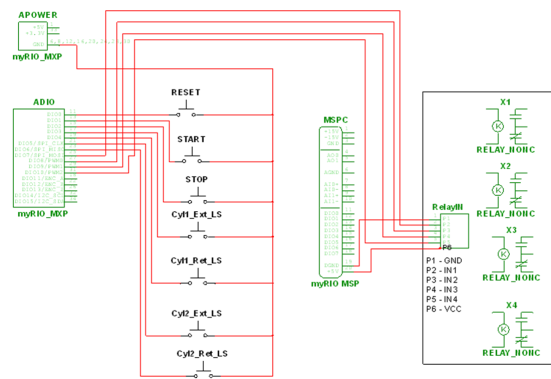
Figure 5 (b): Connection diagram of interfacing push buttons, limit switches and relay board.

Sequential operation of actuators is a common task in assembly lines. This lab exercise is designed to mimic the automation of an assembly line by using two pneumatic cylinders and solenoid valves. An increased interest is observed during the exercise since the lab provides students with an experience of industrial automation by integrating the mechanical components with the electrical components. This further introduces students with a system level programming skill, such as *state machines*. This lab aims at testing students' understanding of digital input and output interfacing learned in previous labs.
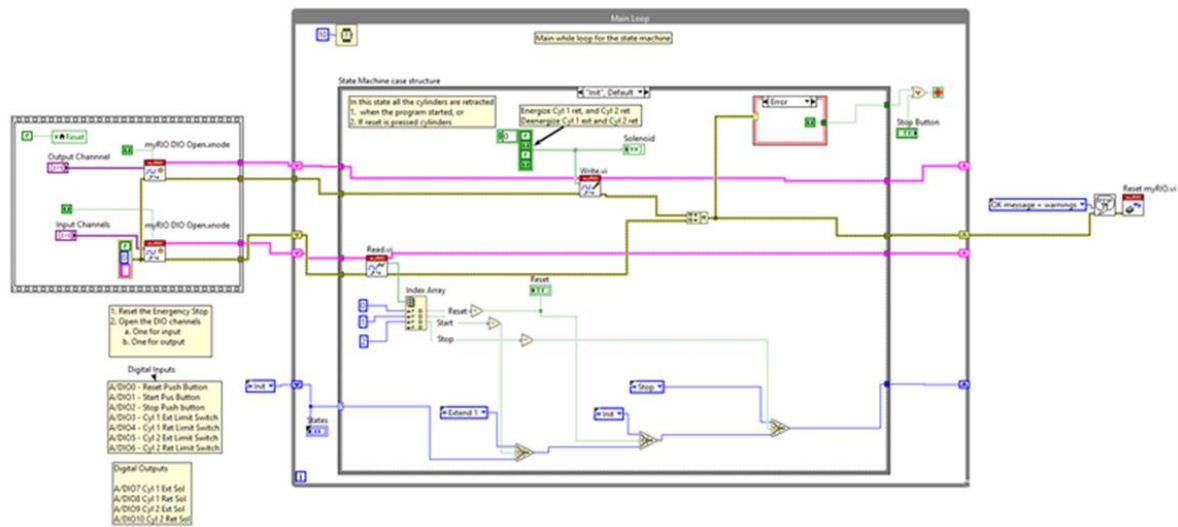

Figure 5 (c): LabVIEW state machine architecture for sequencing pneumatic cylinders.

The pneumatic trainer kit, as shown in Figure 5 (a), is used for the exercise. Seven digital inputs (three push buttons and four limit switches) and four digital outputs are interfaced to the myRIO, as shown in Figure 5(b), to control the solenoids of the direction control valves.

A state machine is used to orchestrate the sequencing action of the cylinders and implemented using the LabVIEW while loop and case structure, as shown in Figure 5 (c). Four states, i.e.,

initial, extension, return, and stop were used to complete the sequencing actions. The state machine was introduced to the students during the lecture. This lab also consists of a pre-lab component in which the students write the LabVIEW code. The pre-lab assignment assisted the students understand the code better and become more interactive during the lab.

Connecting seven switches, as inputs, and four solenoids via relay board, as outputs, increased the complexity of the circuit diagram, as shown in Figure 5 (b), for students with insufficient electrical background. However, both the EET and the MET students were excited about the challenge to test their programs. An overwhelmingly good response was observed from the students when the LabVIEW code worked as desired after debugging some wiring errors. An important aim of the lab is to teach students how to tailor the program to make the device function differently without physically altering the connections. The exercise enabled students to have various automation ideas for their class project.

Lab #6 PWM control of DC motor and digital encoder interface

DC motors are used as actuators in various mechatronics applications. There are various approaches available in the literature to control the DC motors. In general, it requires a driver circuit. H-bridge drivers with PWM signals are commonly used, as shown in Figure 6 (a). This lab activity combines three important concepts taught during the lecture, namely, application of transistors as a switch, interfacing digital hall effect quadrature encoders, and dc motor. The laboratory is designed in two parts. The first part is a pre-lab exercise where the students are asked to write the LabVIEW code. During the hardware implementation, a review of the code and generation of PWM signal is explained.
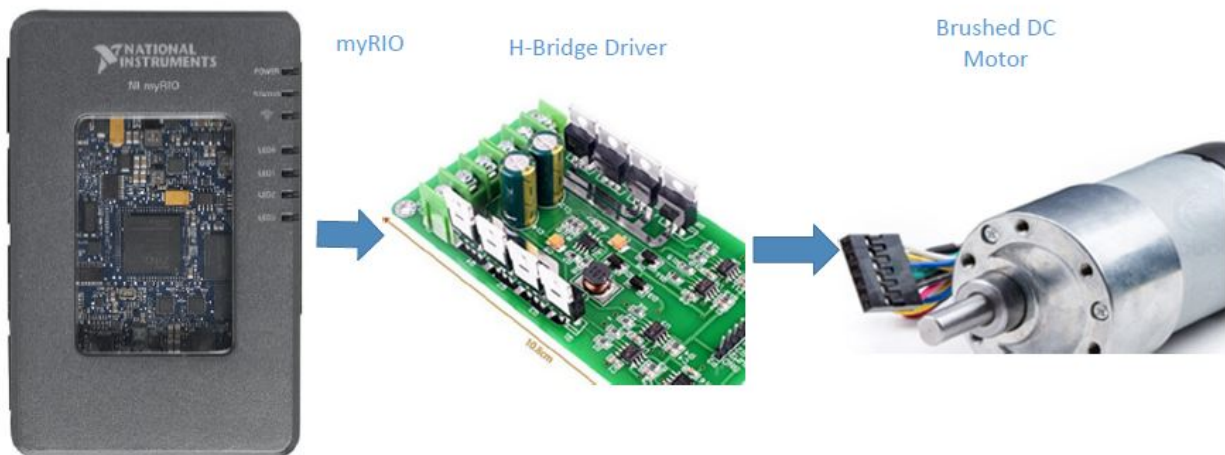

Figure 6 (a): PWM control of DC motor and encoder interface.

The LabVIEW front panel and the circuit diagram for the lab is shown in Figure 6 (b) and (c). One of the goal of the exercise is to teach students the differences between open-loop and closed-loop speed control and PID control.

Lab #7 Full and half stepping of stepper motor Using LabVIEW and NI myRIO

Stepper motors are best suitable for open-loop position control. This laboratory compliments the lecture on stepper motor and various types of stepping techniques. It also focuses on debugging
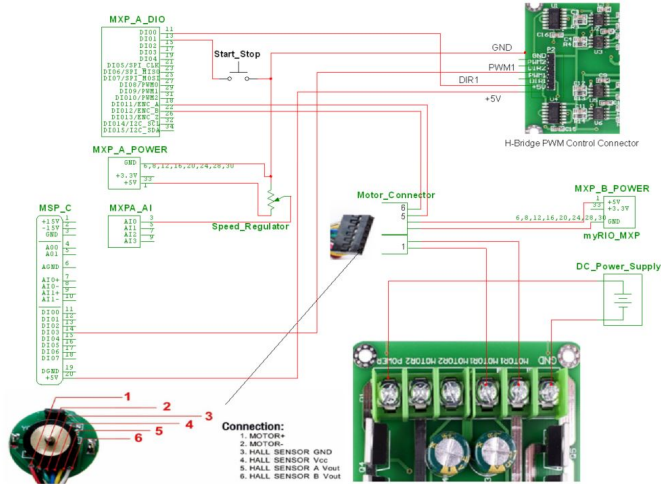
Figure 6 (b) Circuit diagram for dc motor and encoder connection with myRIO.
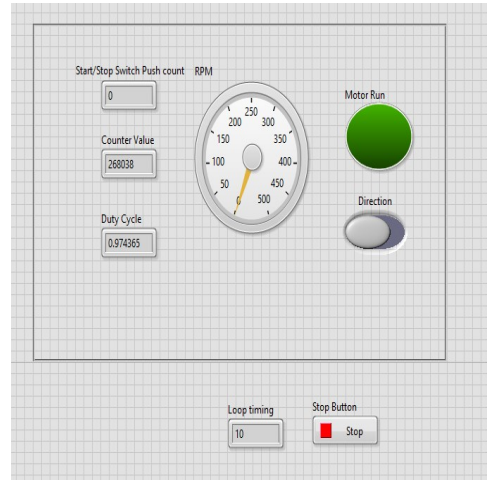

Figure 6 (c) LabVIEW front panel for dc motor control.

LabVIEW codes. In this exercise the students are provided with the LabVIEW code (front panel is shown in Figure 7 (a)). The in-lab activity consists of connecting the stepper motor, driver, and myRIO as per the diagram, shown in Figure 7 (b). There are multiple software bugs, whcih affect the operation of the stepper motor, introduced in the LabVIEW program and the assignment is to debug the code for proper functioning of the motor. The outcome of the experiment is to evaluate
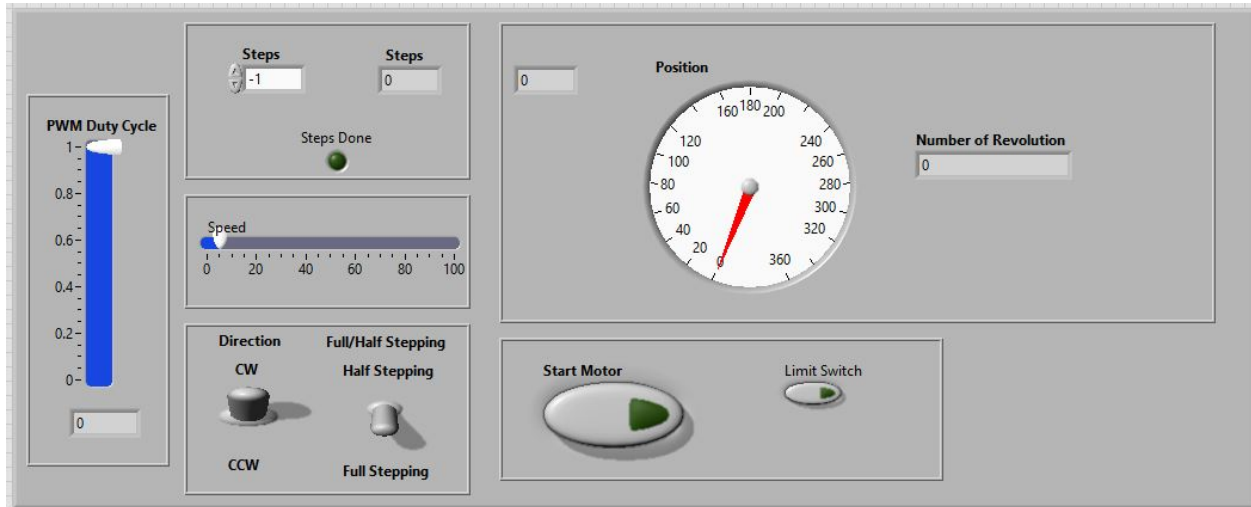

Figure 7 (a): LabVIEW front panel for stepper motor control

students for one of the ABET criterion and judge students' understanding of LabVIEW and correlation between the program and hardware.

Lab #8 Servo and BLDC motor control using LabVIEW and myRIO

Servo motors are widely used for mechatronics application starting form hobby to industrial level projects. The servo motor internal electronics consists of the position sensor (potentiometer) as feedback device and the control circuit. The servo motor and BLDC motors with electronic
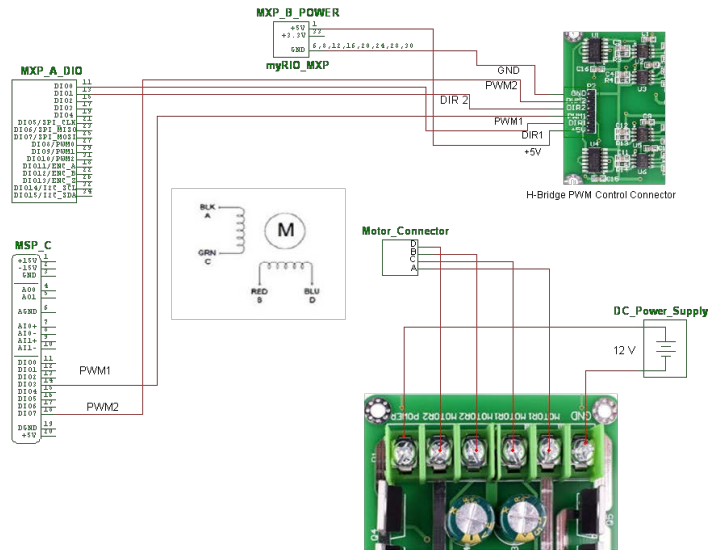
Figure 7 (b): Interface circuit of myRIO, H-bridge and stepper motor.

controller (EC) can be controlled using PWM signal. With wireless remote controllers, these motors are controlled using pulse position modulation (PPM), instead.

Therefore, this lab focuses on interpreting the PPM signal as PWM signal to control both servo and BLDC motor. The LabVIEW front panel and the block diagram for controlling the servo motor are shown in Figure 8(a) and (b), respectively.
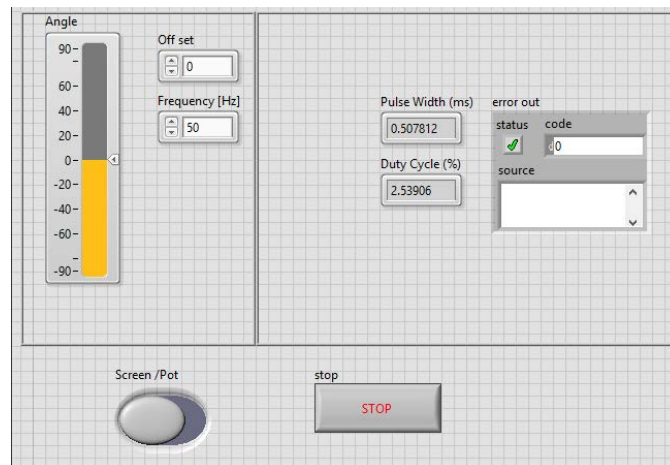

Figure 8 (a) LabVIEW front panel for servo motor.

Course Evaluation

The University Assessment and Testing (UAT) center at Oklahoma State University conducts the survey of the course at the end of the semester both for the lecture and the laboratory session. The university emphasizes online survey to maintain the anonymity of the survey responses. Further, respective faculty member evaluates the student performance in the course as per ABET outcomes. ABET outcomes evaluated for the course are listed in Table 3. Some of the outcomes are judged based on individual performance and others based on team performance.
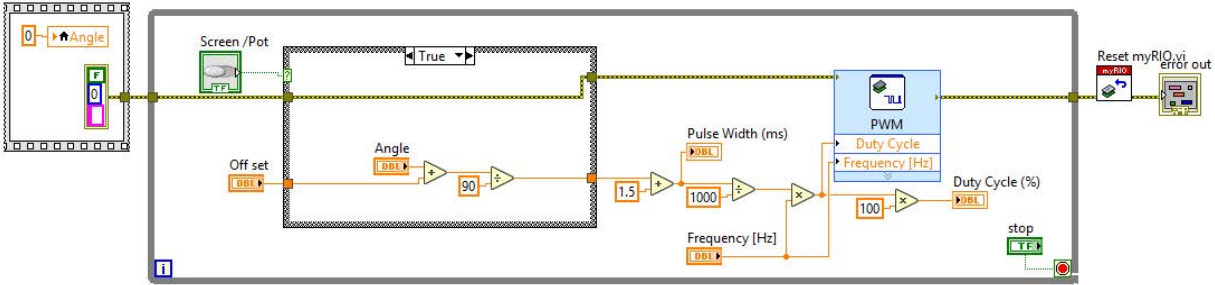
Figure 8 (b) LabVIEW block diagram for servo motor control.

Table 3: ABET Program Outcomes

Outcomes
(a) Application of knowledge, techniques, skills, and modern tools of the discipline
(b) Application of knowledge of mathematics, science, engineering, and technology
(c) Ability to conduct standard tests and measurements
(d) Ability to design systems, components, or processes
(e) Ability to function effectively as a member or leader on a technical team
(f) Ability to identify, analyze, and solve broadly-defined engineering technology problems
(j) Knowledge of the impact of engineering technology solutions in a societal and global context

Students' feedback of the course is listed in Table 4. The course evaluation uses a 4.0 scale. There were eight students enrolled in Fall 2018 and survey responses shows that 97% of the students responded the course is worthwhile for them and overall a good course. The student ranking of the professor is given in Table 5. Instructor evaluation uses a 5.0 point scale. The overall instructor appraisal is 4.88.

Table 4: Student views on laboratory section of the course (4 point scale)

Questions	Score (8)
I learned a lot in this course	3.88
Workload was appropriate for the credit hours	3.75
Assignments were relevant and useful	3.88
Testing and evaluation procedures were good	3.88
Students were adequately involved	3.75
This course was worthwhile to me	3.88
Overall, this was a good COURSE	3.88

Some of the student comments on the course are as follows:

- I really enjoyed the course, as I was able to see the correlation between electrical and mechanical components first hand.

Table 5: Student ranking of the instructor (5 point scale)

Questions	Score (8)
Preparation and organization	4.75
Effort devoted to teaching	5
Presentation of materials	4.88
Knowledge of subject	4.88
Ability to explain subject matter	4.75
Positive attitude toward students	5
Overall INSTRUCTOR appraisal	4.88

- I would say don't spend so much time with the review stuff at the beginning, it just seems redundant. That way there is more time to explain the new material such as the transistor portion of the course. Would have liked to spend more time on that subject.

- I would have liked a little more repetition on some of the harder concepts in the homework. BJTs and MOSFETs for example

- Beginning of the course was a little hard to understand the lab and assignment in the software. It would be really helpful to have a video explaining a little bit about the software. As MET students, we had videos for the courses that use a software which helps to understand a little bit. All in all, it was very beneficial course for me and I think it will help me in the future.

Based on the students' comments, more videos will be included in both laboratory and lecture sections. The comment on repetitive portion of the course is due to the diverse background of students enrolled in the course. We plan to reduce the repetition by engaging students with assignments on prerequisites in future semesters.

Conclusions

The paper presented the laboratory activities developed for the Fundamental of Mechatronics course offered in the Division of Engineering Technology of Oklahoma State University. The course objective, pedagogical approach, and course evaluation are presented. The laboratory activities were designed for students with minimal or no programming experience. Students are taught not only the fundamental principles behind the sensors but also their interfacing and control via myRIO as a micro-controller. The use of the graphical programming language helped students understand the interfacing and control logic and motivated them to learn further on the subjects. We plan to continuously improve the course to keep it updated with the latest technology. A section on programmable logic controllers as an alternative controller will be introduced in future semesters.

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