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A Low-Cost Hands-On Instrumentation Course for EET Students

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Abstract

The design of a low-cost hands-on instrumentation course for electronics engineering technology students is presented in this paper. The course incorporates experiment design and problem-based learning as pedagogical tools. Course objectives include: applications of sensors and transducers, and design of associated interface circuits; laboratory experience integrating sensors, and data acquisition hardware and software; and experiment-design project implementation and reporting experience. This paper presents the course format including the typical content, laboratory setup and experiences, and student-initiated experiment-design project details. Course-embedded assessment data supporting the course objectives and associated student outcomes are also reported.

Introduction

The ability to conduct and design experiments is rated as one of the most desirable technical skills of engineering and engineering technology graduates[1]. Specifically, the referenced survey indicates that employers want graduates with a working knowledge of data acquisition, analysis and interpretation, and an ability to formulate a range of alternative problem solutions. Additionally, many employers of our EET graduates are in the manufacturing and testing sector of the industry providing additional motivation for a hands-on instrumentation and data acquisition course. This course consists of two hours of lecture and three hours of laboratory per week. Students have had courses in electrical circuit analysis and analog electronics before taking this course, and a course in digital electronics is a co-requisite. In terms of the curriculum, the first three weeks of the fourteen-week semester are devoted primarily to LabVIEW programming. During the next nine weeks, concepts and integration of sensors and actuators, interface electronics, and data acquisition and instrument control hardware/software are covered. The final two weeks are dedicated to student-initiated experiment-design projects.

For pedagogical reasons, the problem-based learning (PBL)[2,3] was adopted for this course. With PBL, students are empowered to self-direct their educational experience by designing experimental systems and/or subsystems against given specifications. It is an instructional method which uses real-world problems to facilitate students' critical thinking and problem solving skills while accomplishing the course objectives. Students get involved and take responsibility for their learning experience, and the instructor becomes a resource. The purpose of implementing PBL is to motivate the student to integrate and utilize their knowledge. In this instrumentation and data acquisition course, PBL is applied to laboratory experiments and student-led experiment-design[4] projects. Recent proliferation of biomedical instrumentation[5-7] contributed to the development of a heart-rate monitoring system as one of many experiment-design projects developed and implemented by students.

The following sections present a summary of course-level assessment approach, the curriculum and laboratory setup, sample laboratory experiences and experiment-design projects, an assessment summary, and a conclusion.

Course Objectives, Outcomes, and Assessment

The three main objectives of this course are: understanding the principles and applications of sensors and transducers, and the design of associated interface circuits; providing laboratory experience in integrating sensors, interface electronics, and data acquisition hardware and software; and providing hands-on instrumentation project design, implementation, and reporting experience. The mapping between these three course objectives and student outcomes as defined by the Criteron-3 of ABET-ETAC[8] is shown in Table I. Definitions of specific ABET-ETAC student outcomes[8] applicable to this course are listed below for the sake of completeness.

- *Outcome a:* Ability to select and apply the knowledge, techniques, skills, and modern tools of the discipline to broadly-defined engineering technology activities,
- *Outcome b:* Ability to select and apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require the application of principles and applied procedures or methodologies,
- *Outcome c:* Ability to conduct standard tests and measurements; to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes,
- *Outcome d:* Ability to design systems, components, or processes for broadly-defined engineering technology problems appropriate to program educational objectives,
- *Outcome e:* Ability to function effectively as a member or leader on a technical team,
- *Outcome f:* Ability to identify, analyze, and solve broadly-defined engineering technology problems,
- *Outcome g:* Ability to apply written, oral, and graphical communication in both technical and nontechnical environments; and an ability to identify and use appropriate technical literature,
- *Outcome h:* Understanding of the need for and an ability to engage in self-directed continuing professional development,
- *Outcome i:* Understanding of and a commitment to address professional and ethical responsibilities including a respect for diversity, and
- *Outcome k:* Commitment to quality, timeliness, and continuous improvement.

Table I: Mapping of Course Objectives to Student Outcomes

Course Objectives	Supported Student Outcomes (per ABET-TAC Criterion-3)
Principles and applications of sensors and transducers, and associated interface circuit design	a, b, d
Laboratory experience integrating sensors, interface electronics, and data acquisition hardware and software	a, b, c, d, e, f, g, h, i, k
Hands-on instrumentation project design, implementation, and reporting	a, b, c, d, e, f, g, h, i, k

Students are assessed for course objectives and associated outcomes using various direct and indirect assessment tools. Additionally, course-embedded direct assessment of objectives and university-level end-of-semester faculty and course indirect assessment provide valuable input to the overall course assessment and continuous improvement process. Results from various direct and indirect assessment instruments are archived and processed annually to generate action items used as input to the course's continuous improvement process.

Course Format

This three-credit course meets for two one-hour lectures and one three-hour laboratory per week. The first three weeks of the fourteen-week semester are primarily devoted to LabVIEW programming. During the next nine weeks, the concepts and integration of sensor and transducers, interface electronics, and data acquisition and instrument control hardware/software are covered. The final two weeks are reserved for student-initiated experiment-design projects, providing an opportunity for students to integrate their knowledge in instrumentation hardware and software via developing a project of their choice. The distinction between lecture and laboratory hours is blurred in this course since the course is exploration and design driven.

For the first few labs, students work individually to become sufficiently proficient with LabVIEW programming. Since the class size is capped at 24 students, individual programming experience is supported by twelve desktop and twelve laptop computers. Once the hardware and software integration starts, students work in a group of two or three. It is observed that most students pick up the programming part relatively easily, and the progress slows down a bit when hardware development starts even though students have had an electronics course in the previous semester. Typical course content for the instrumentation course is described next.

Typical course content:

- **Fundamentals of programming logic:** Virtual instruments, indicators/controls; front panel/block diagram; data types and data flow programming; structures, clusters, arrays, and loops; graphs and charts; subVIs; and file I/O.
- **Sensors and transducers:** Resistive, capacitive, and inductive sensors; temperature sensors; position, displacement, and speed sensors; force and pressure sensors; vibration and acceleration sensors; proximity and presence sensors; electro-optical sensors; flow and flow-rate sensors; and liquid-level and humidity sensors.
- **Signal conditioning and data acquisition:** Analog-to-digital and digital-to-analog converters; sampling rate, multiplexing, resolution, range, and code width; grounding, isolation and noise; single-ended and differential measurements; attenuation, amplification, and filtering; excitation and linearization; impedance mismatch and loading; signal transmission (voltage vs. current loop); and hardware architecture of a modern multi-function data acquisition device.
- **Instrument control:** Components of an instrument control system (GPIB and RS-232); detecting and configuring instruments; and instrument drivers.
- **Instrumentation system design:** Design specifications; functional block representation; design, debugging, and testing; interpretation and presentation of data; user interface; temperature control system design; motor speed control system design; and student-initiated experiment-design projects integrating sensors/transducers, actuators, interface electronics, and data-acquisition hardware and software.

Laboratory Setup

The laboratory has twelve stations to accommodate 24 students. Each station is equipped with a desktop PC, and GPIB/RS-232 interfaced instruments such as digital multimeter, triple output laboratory power supply, arbitrary function generator, and two-channel digital oscilloscope. The instrumentation and data acquisition specific software and hardware are briefly described below.

Software:
LabVIEW 2012[9]

NI-myDAQ[10] data acquisition device: The key features of this USB interfaced portable and low-cost device, easily purchased and used by students in their dorm room, is listed below along with a pictorial view shown in Figure 1.

- 2 analog inputs (configurable as high-impedance differential voltage input or audio input), sampling up to 200 kS/s per channel
- 2 analog outputs (configurable as voltage output or audio output), update rate up to 200 kS/s per channel
- 8 digital I/O channels, each line is a Programmable Function Interface (PFI). Accordingly, counter, timer, pulse width measuring/generation, and quadrature encoding functions are available.
- Power supplies: There are three power supplies available (+5 V, +15 V, and -15 V). The total power available is limited to 500 mW.
- Digital multimeter: Can be used to measure dc and ac voltages (limited to 60 VDC and 20 VAC_{RMS}), dc and ac currents (limited to 1 A), resistance, and diode voltage drop; measurements are software-timed.

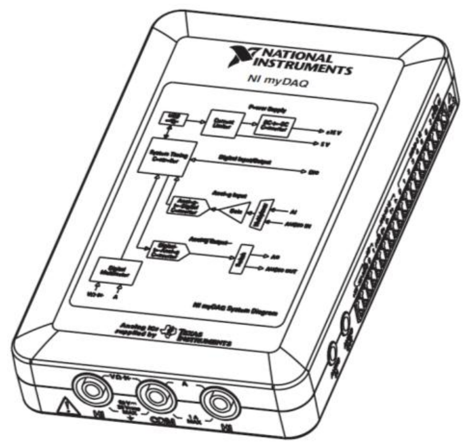


Figure 1: A pictorial view of the low-cost and portable NI-myDAQ[10] device.

GPIB controller board:
- IEEE 488.2 compatible architecture
- Eight-bit parallel, byte-serial, asynchronous data transfer
- Maximum data transfer rate of 1 MB/sec within the worst-case transmission line specifications

Signal conditioning accessory:
The accessory protoboard available in the laboratory is shown in Figure 2 and connects directly to the NI myDAQ device. This accessory[11] consists of a prototyping space as well as each I/O line from NI myDAQ broken out through quad contact blocks to make wiring easier. This breakout board includes a breadboard for solderless prototyping and a 9 V battery holder to access a supplemental voltage source.

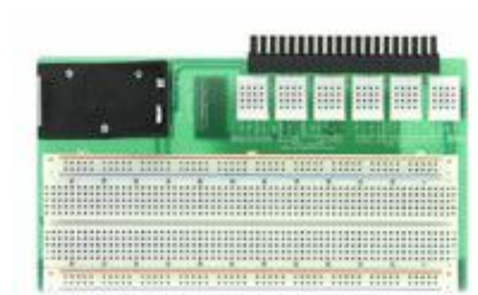


Figure 2: A pictorial view of the accessory protoboard[11] for the NI-myDAQ device.

Typical Laboratory Experiences

Laboratory experiences are grouped in four basic categories: software development only, digital and analog I/O integrating sensors and transducers, On/Off control application, and student-initiated experiment-design project. As mentioned earlier, the final two weeks of the course are dedicated to student-initiated experiment-design projects.

Software development (LabVIEW programming):
The first three laboratory periods of the semester are dedicated to gaining LabVIEW programming experience. After a brief introduction to the programming environment, students are introduced to case structure, while loop, for loop, formula node, and graphing functions (waveform chart, waveform graph, and XY graph). By the end of the first lab, students develop applications such as capacitor charging in a first-order circuit as shown in Figure 3. Students continue to learn additional features such as shift register, time delay, local variable, and array operations. A traffic light controller designed using local variables and multiple case structures is shown in Figure 4, analyzing and graphing frequency response of an active low-pass filter using layered logic is shown in Figure 5, and the use of various array operations is learned via implementing a greatest common factor (GCF) algorithm shown in Figure 6.

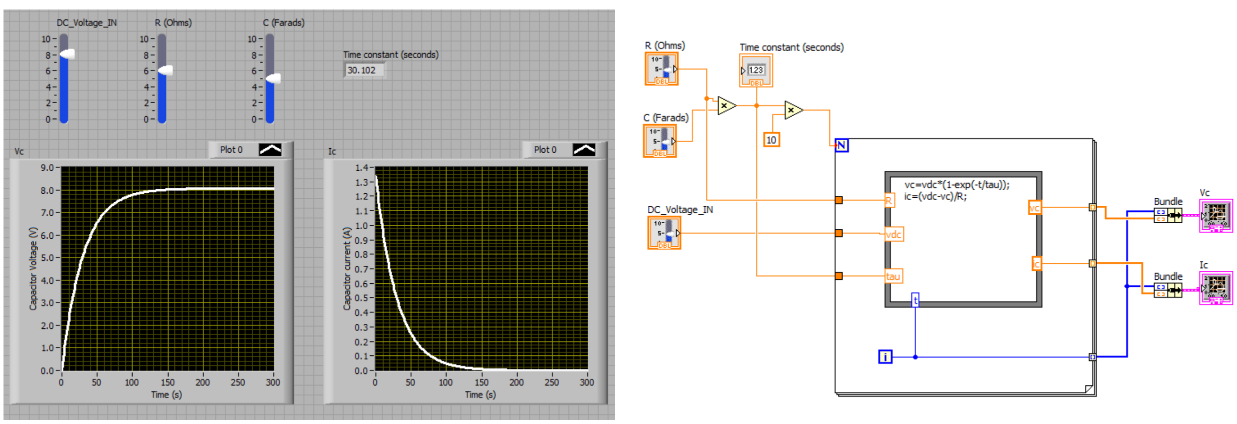


Figure 3: Front panel and block diagram of an R-C charging circuit.

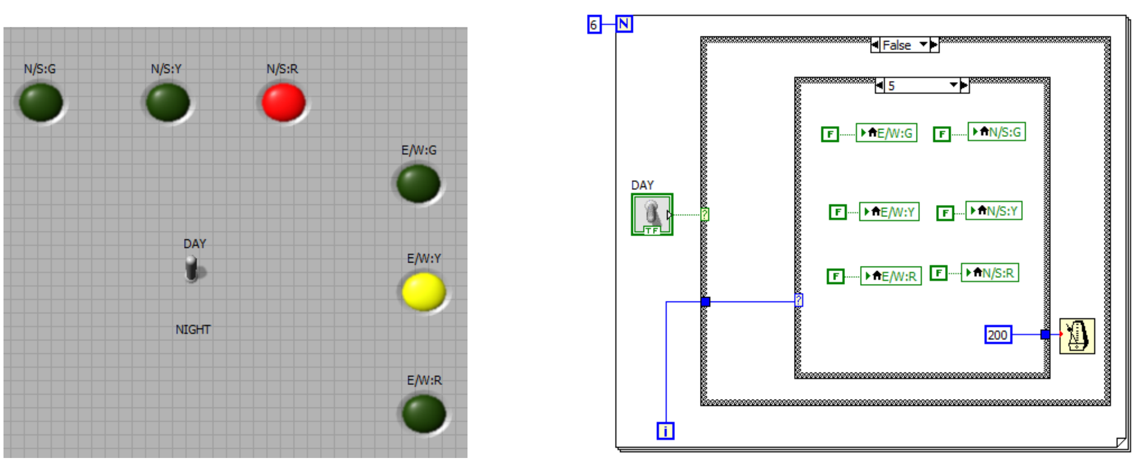


Figure 4: Front panel and block diagram of a traffic-light controller.

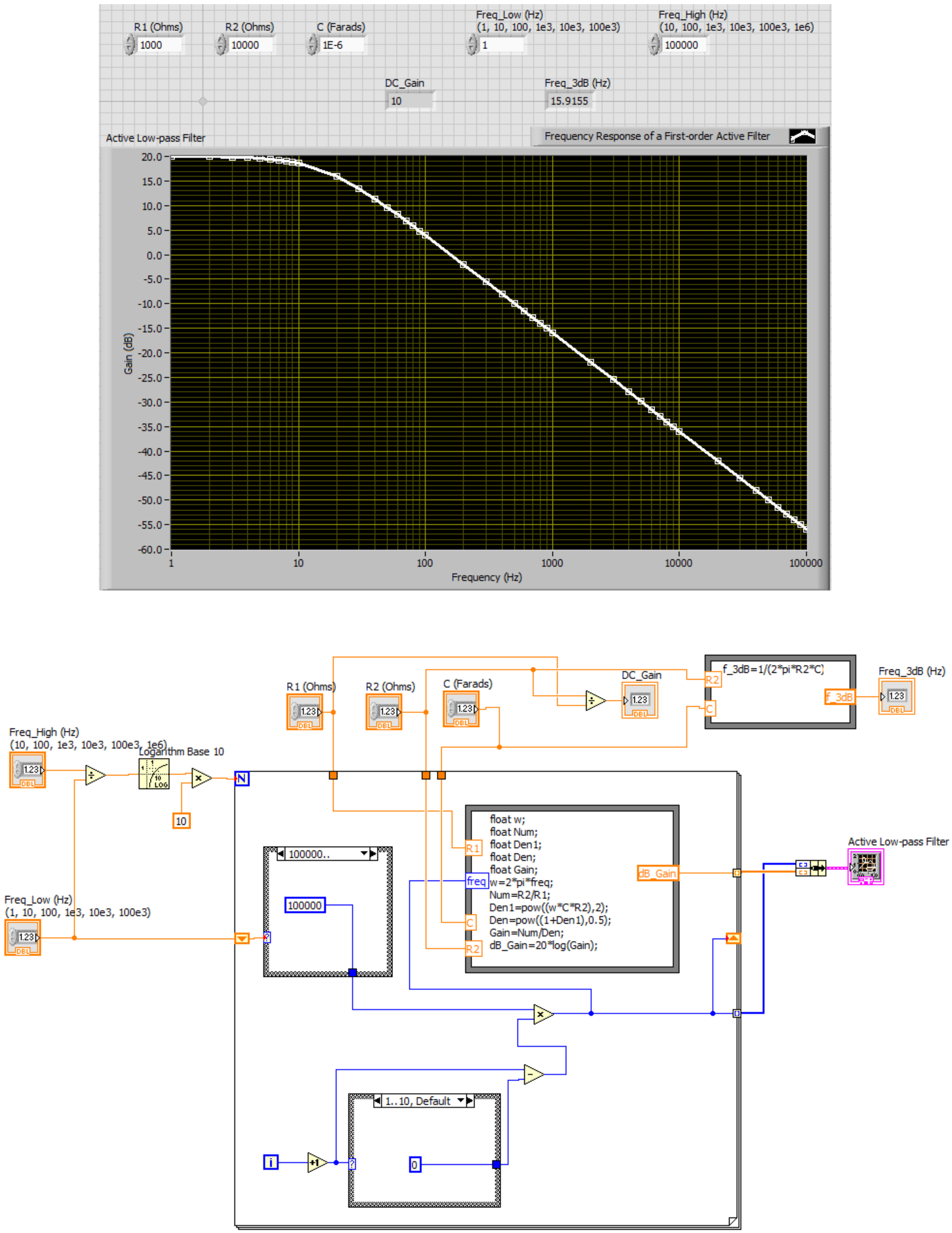


Figure 5: Front panel and block diagram for the frequency response of an active low-pass filter.

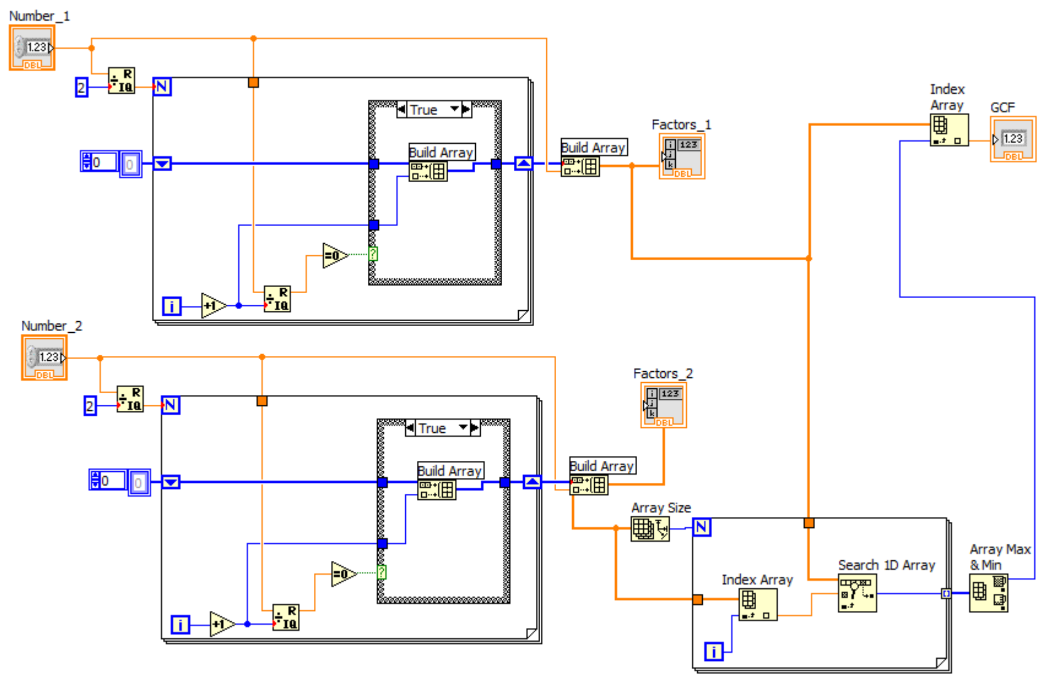


Figure 6: Block diagram for implementing a greatest common factor (GCF) algorithm.

<u>Digital and analog I/O integrating sensors and transducers:</u>
The first data-acquisition (DAQ) experience with digital I/O is executed through the design of a traffic light controller using green, yellow, and red physical LEDs for E/W and N/S directions including flashing red and yellow physical LEDs for night time operation. The first analog I/O experiment is to design a system to calculate the value of an unknown resistor. Additional I/O experiments include the use of temperature sensors (e.g., solid-state, thermocouple, and RTD), photoelectric sensors for counting, infrared distance sensors, relative humidity sensors, and H-bridge circuits for motor direction reversal. Laboratory experiments also include I-V characterization of basic semiconductor devices such as switching diodes, zener diodes, and LEDs. Since students receive enough experience with LabVIEW programming during the previous weeks and are well versed with basic electronic circuit design, they are provided with minimal instruction for the digital and analog I/O experiments integrating various types of sensors and transducers.

<u>On/Off control application:</u>
The final laboratory experiment focuses on designing an on/off controller based temperature control system. A block diagram representation of the system is shown in Figure 7. Students first design a temperature control system for a reference temperature of 60^{o}C using an IC temperature sensor (LM35) and other discrete components[12]. The design is thoroughly tested against ambient as well changing set point and load conditions. The concept of system time-constant is introduced at this stage. Next, the discrete on/off controller with hysteresis is replaced with the software on/off controller. This is implemented in LabVIEW and the myDAQ device is used to input the amplified temperature signal and output the control signal to the MOSFET driver circuit.

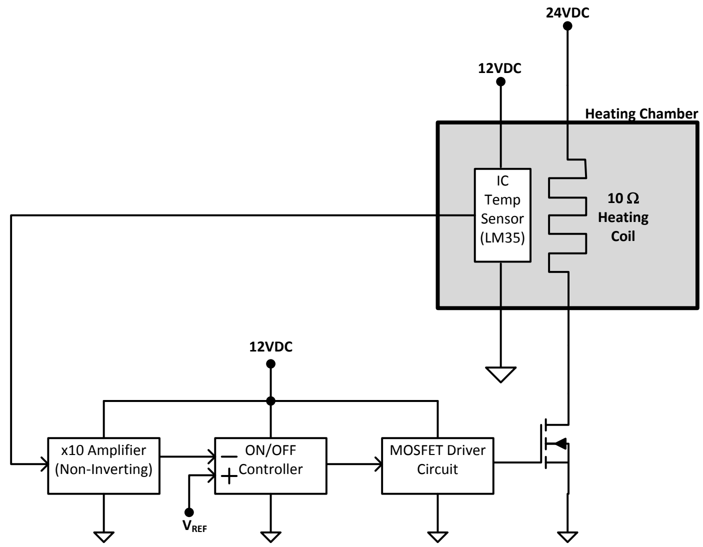


Figure 7: A temperature control system implementation using an on/off controller.

<u>Student-initiated experiment-design projects:</u>

The last two weeks of the semester are dedicated to student-initiated experiment-design projects carried out in a group of two or three students. This is an opportunity for students to integrate the software and hardware knowledge they have gained during the first twelve weeks of the semester, and use their creativity to develop an experiment-design project in a friendly yet competitive environment. Each group of students is required to submit a pre-proposal with two experiment-design project ideas. This is followed by a student-led classroom discussion of the proposed ideas. At the end of the discussion period, each group either selects or is assigned one of the proposed ideas to pursue as the experiment-design project. Next, the students are required to submit a detailed proposal including project implementation steps (supported by major outcomes and specifications), I/O interface drawing, circuit schematics, parts list with vendor/price information, LabVIEW program flow chart, and project completion schedule. Students are responsible for selecting the necessary sensors, transducers, and actuators. Each group is typically allocated a budget of $75 for purchasing project-specific parts unavailable in the laboratory. Students also use the reasonably well-equipped departmental shop for fabrication and metal/wood work to support their projects. A formal presentation and a final report are due at the end of the semester. Some of the projects which were successfully completed during the fall-2012 semester are: a heat-pump system, electronic fitness monitoring, tilt control system, mock police radar system, voice activated box, and automated garage door system. Two of these projects are described next.

Simulated heat-pump system

The purpose of this experiment is to use the Peltier, or thermoelectric, effect to change the temperature of an aluminum block. The temperature in the block is controlled using a thermoelectric device (TE) between itself and a heat sink. The LabVIEW program and associated interface circuitry control the heating and cooling, along with the acquisition of temperature data from the block and the ambient. The TE device creates a voltage when there is a difference in temperature between the top and bottom sides, but in this experiment a voltage is applied to the TE device causing a temperature difference between the top and bottom sides. As shown in Figure 8, this effect will transfer heat up or down depending on the current direction. The thermoelectric effect has many useful applications; for example, the ability to transfer energy from one medium to another is used in heat pumps for heating/cooling and electronic cooling systems. The biggest advantage of the Peltier effect is that it doesn't use any liquid and is easy to transport since it has no moving parts. In this experiment-design project, a TE module from Mouser[13] is used to cool and heat an aluminum block from 80°C to about -15°C, with an ambient temperature of about 23°C.

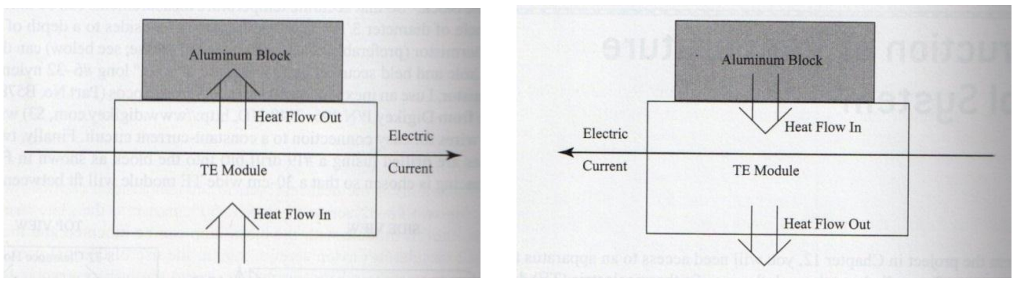


Figure 8: Heat flow direction reversal by changing current direction in a thermoelectric module.

The circuit implementation of the heat-pump system is shown in Figure 9. There are two analog inputs (for sensing ambient and Al block temperatures) and two digital outputs (one to turn on/off a MOSFET-based high-side switch implementing on/off control, and the other to energize/deenergize a relay coil implementing current-flow direction control for the TE module). Based on the ambient and set point temperatures, the control logic decides either the heat or cool mode (via the relay contacts). The heat/cool mode dictates the current flow direction in the TE module.

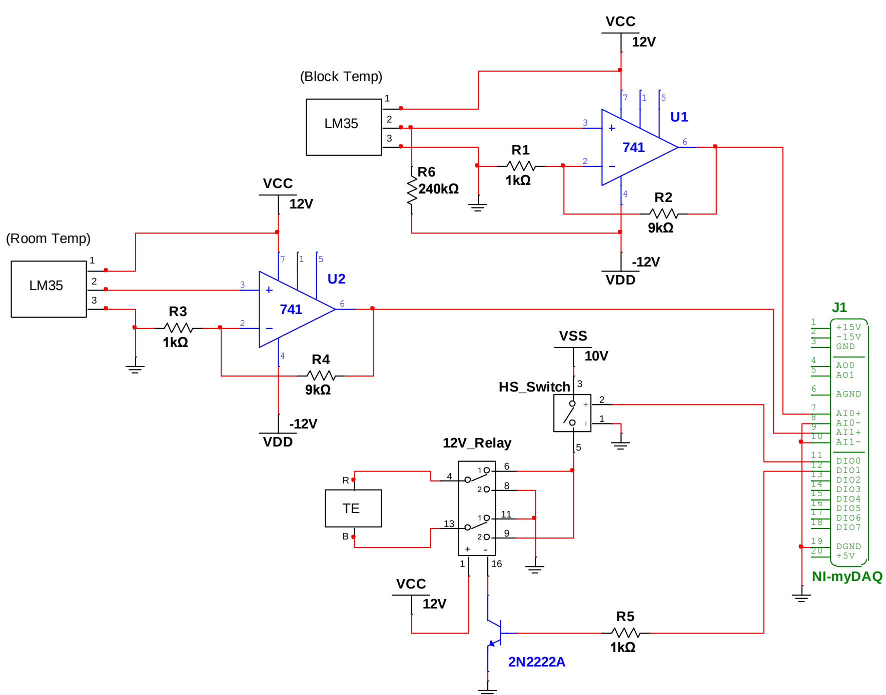


Figure 9: Analog and digital I/O interface and control electronics for the heat pump system.

Once the heat/cool mode is set and the desired set point temperature is hit via continuous heating/cooling, the on/off controller kicks in and maintains the temperature by turning on/off the power to the TE module via the high-side switch. The system is able to achieve any set point temperature in the 80°C to -15°C range, and maintain it within ±0.75°C of the set point. A pictorial view of the heat-pump experiment-design project and the associated LabVIEW control logic are shown in Figure 10, and the corresponding front panel is shown in Figure 11. As shown in the pictorial view of Figure 10, a 12 VDC fan placed under the heat sink runs continuously to help with thermal exchange for both hot and cold modes.

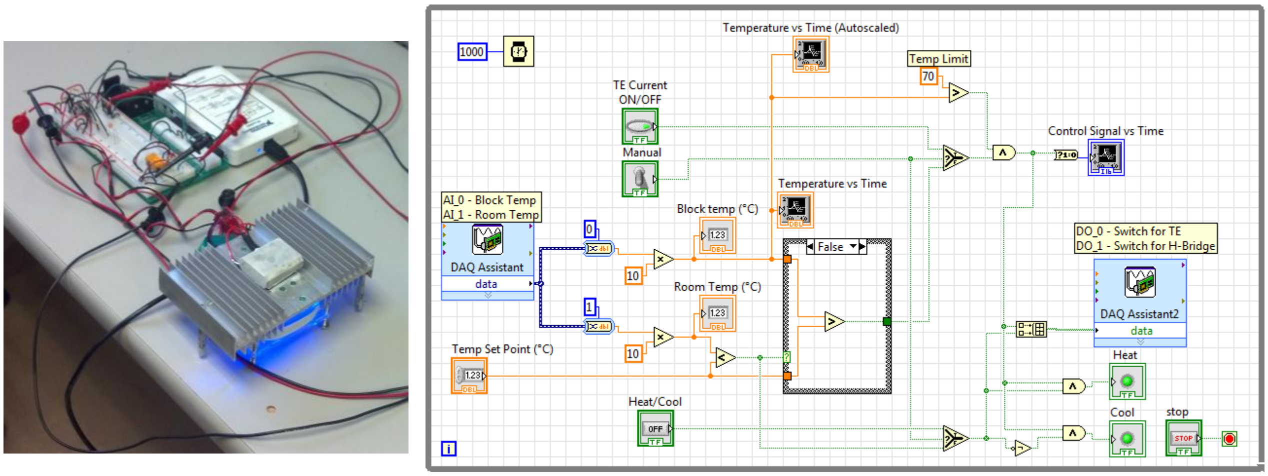


Figure 10: A pictorial view of the implemented heat pump system (left) and the associated LabVIEW control logic (right).

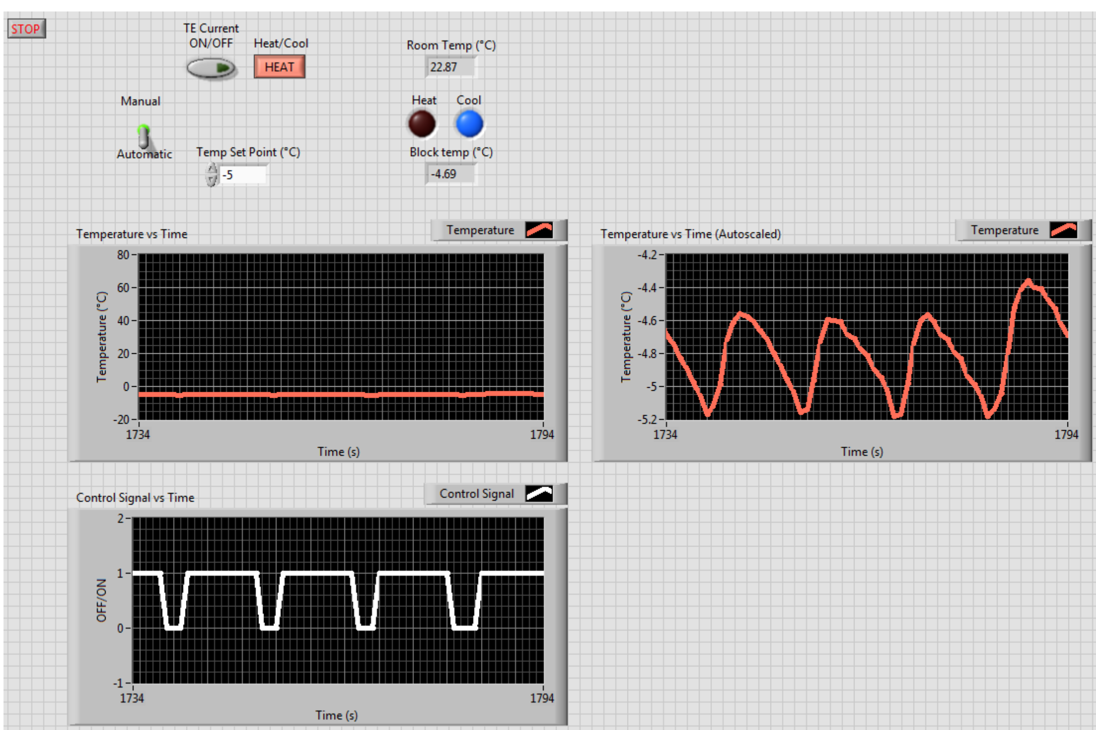
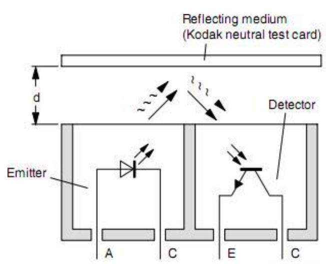


Figure 11: Front panel view of the heat pump system for a set point temperature of -5°C.

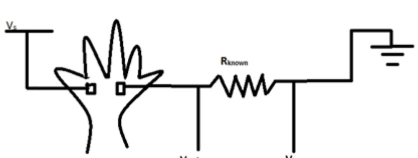
Electronic fitness monitoring

This project acquires and processes biophysical data for heart rate and skin resistance. The measurement system outputs skin resistance, heart rate in BPM (beats per minute), and heart rate status (e.g., resting, warm up, fat burning, cardio, and hardcore training). Additionally, it actuates a cooling fan for sweat control. For this application, the two contractions that make up the heart beat (atrial systole and ventricular systole) are used. Because of these contractions, the amount of oxygenated blood changes in the extremities, for example in a fingertip. As shown in Figure 12(a), a reflective optical sensor (e.g., TCRT1010[14]) with a photodiode emits an infrared light which is absorbed by the deoxygenated blood in a fingertip whereas the oxygenated blood reflects the infrared light back into a phototransistor. After inputting the amplified phototransistor output to the LabVIEW environment via data-acquisition hardware, it is relatively easy to calculate the heart rate by focusing on the peak detection and/or frequency component of the input signal. Another variable of interest is the skin resistance; it is largely dependent on how much moisture is in the skin. If skin is dry the resistance goes up but if a person sweats (e.g., due to exercising or stress) the resistance goes down. As shown in Figure 12(b), using a pair of electrodes on the palm of your hand and a voltage divider circuit, it is easy to calculate the skin resistance. The I/O connections to the myDAQ device and the associated interface and sensing circuits are shown in Figure 13. For the skin resistance measurement setup, a voltage divider circuit with a 2 VDC bias and a 2 kΩ series resistance were used to limit the maximum current through the skin to 1 mA. This is acceptable since a current level below 5 mA through the skin is generally considered safe.

The front panel displays for the heart rate signal and the skin resistance are shown in Figure 14. The displayed heart rate is 88 BPM and falls under the *resting* category. The displayed skin resistance is in the 60-100 kΩ range as it was changed by breathing onto the palm and also by using a fan to reduce the sweat level of the palm. Block diagram implementation for the heart rate calculation logic, including the use of low pass filter and peak detector blocks, is shown in Figure 15.



(a) Reflective optical sensor for heart rate monitoring



(b) Skin resistance measurement circuit

Figure 12: Heart rate and skin resistance sensing.

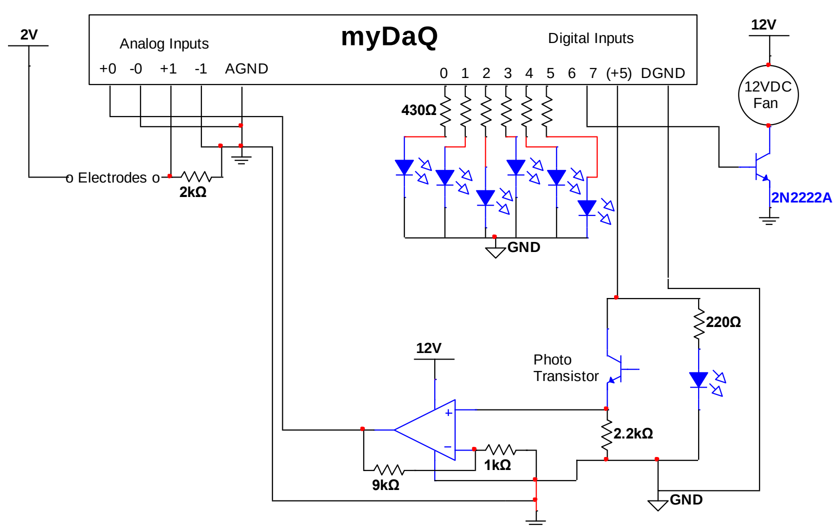


Figure 13: I/O interface and associated sensing electronics for the electronic fitness monitoring system.

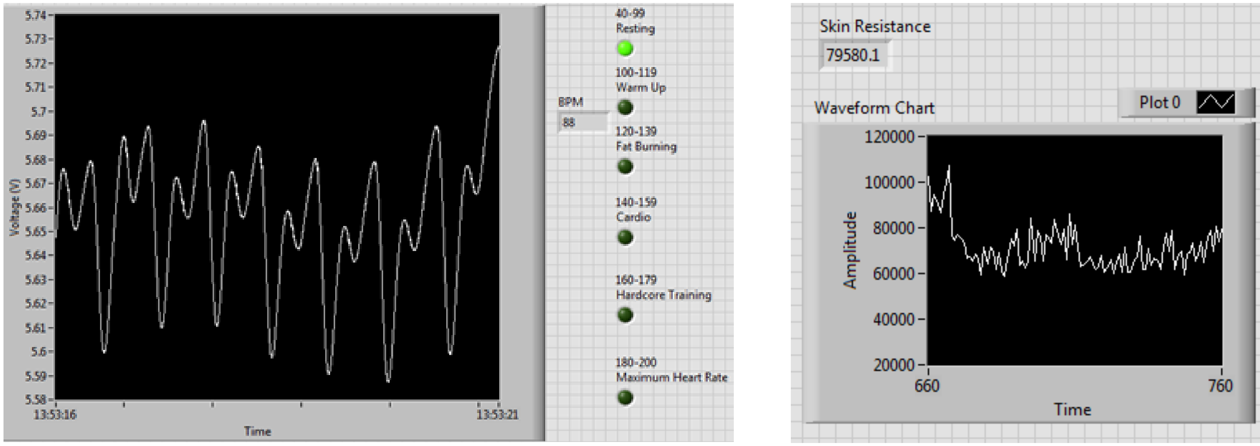


Figure 14: Front panel views of the heart rate (left) and skin resistance (right) displays.

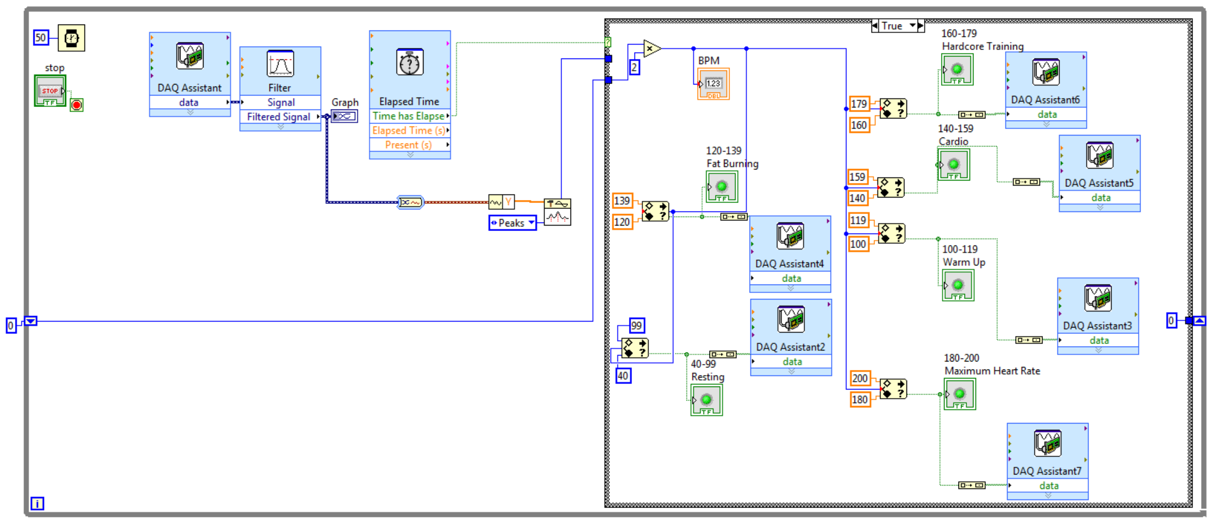


Figure 15: Block diagram implementation of the heart rate monitoring logic.

Course Assessment

In addition to course-embedded direct assessment, indirect assessment of course objectives and associated student outcomes was conducted. Student responses are summarized in tables II and III for course objectives and student outcomes, respectively.

Table II: Student Assessment of Course Objectives

Course Objective	(Excellent + Good) responses based on student survey
Your understanding of the principles and applications of sensors and transducers, and ability to design associated interface circuits	95%
Your laboratory experience integrating sensors, interface electronics, and data acquisition hardware and software	89%
Your hands-on instrumentation project design, implementation, and reporting experience	95%

Table III: Student Assessment of Student Outcomes

Student Outcome		(Excellent + Good) responses based on student survey
a	Your ability to select and apply the knowledge, techniques, skills, and modern tools of engineering technology to instrumentation system applications	95%
b	Your ability to select and apply mathematics, science, engineering, and technology concepts and principles to instrumentation system design	89%
c	Your ability to conduct standard tests and measurements; and to conduct, analyze, and interpret experiments; and to apply experimental results to improve processes	79%
d	Your ability to design instrumentation subsystems and systems	84%
e	Your ability to function effectively as a member or leader of a technical team	100%
f	Your ability to identify, analyze, and solve applied electronic instrumentation problems	84%
g	Your ability to apply written, oral, and graphical communication in technical environment; and an ability to identify and use appropriate technical literature	79%
h	Your understanding of the need for and an ability to engage in self-directed continuing professional development	84%
i	Your understanding of and a commitment to address professional and ethical responsibilities including a respect for diversity	84%
k	Your commitment to quality, timeliness, and continuous improvement	95%

Acccording to student responses, it can be stated that the course is able to meet its objectives. Regarding the laboratory experience, students did suggest that the lab handout should be distributed at least three days before the scheduled lab instead of the day before as it was done. This constructive feedback is logical since the laboratory experiences in this course are design-orineted and require significant prelab effort; this sugggestion will be implemented during the next course offering. Students' perception of the course outrcomes is also generally very positive. Additionally, students did indicate that they enjoyed the end-of-semster two week experiment-design project the most as this experience integrates the hardware and software knowledge gained throughout the semester and introduces them to new sensors and technologies. Students also enjoyed the experience of learning from projects carried out by other students and helping each other in solving technical issues encountered during the project implementation phase. The end-of-semester project presentation and demonstrartion experience, in a friendly yet competitive environment, was also highly valued by students.

Summary

Experience with the development of a low-cost instrumentation and data acquisition course embedding problem-based learning is presented. A few students struggled at the beginning of the semester, as this was their first experience with problem-based learning and design-oriented laboratory experiences. It was also observed that many students did not have to design, debug and test a system that had multiple functional blocks in previous courses. The majority of students had difficulty breaking the design into functional modules and designing and testing them separately before putting them together. Improving student competence in this area will be incorporated at the next offering of this course. Based on student feedback, their experience in this design oriented and project based instrumentation course has been very rewarding and challenging.

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