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Developing a Laboratory Course in Sensors and Data Acquisition for Agricultural Engineering*

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This paper reports an endeavor to outfit a laboratory for a new course that teaches physical process variable measurements, signal conditioning, data acquisition using computers, data processing, and transmission and communication of measurement results. Major effort was spent on designing and building new instrumentation test stands. Each test stand has a computer, a data acquisition system, various transducers for pressure, flow, and temperature, and several other process control components such as valves, a pressure accumulator, a heat exchanger and heaters. The test stands are self-contained, modular, movable, and can be used wherever there is electric power. Internet connection allows monitoring and control of the test stands from anywhere in the world. Students write graphical programs to acquire, process, and present data. Students have applied the skills gained in the course to research and industry. The course has helped one of its students win an international scholarship. Initiated at Purdue University, the course has been taught at a university in Brazil.

Keywords: sensors; data acquisition; agricultural engineering.

INTRODUCTION

CURRICULUM ADAPTATION in response to constituent feedback is encouraged by ABET as part of the continuous improvement of the curriculum. The Agricultural and Biological Engineering (ABE) Department at Purdue University conducts periodic curriculum reviews every few years. In 1996, in response to surveys by mail and telephone calls, ABE department alumni expressed the opinion that ABE graduates needed better skills in measurement instrumentation and data acquisition. Motivated by this feedback, the department started a course entitled Instrumentation and Data Acquisition in the fall semester of 1998. The course contents were selected from topics recommended by engineers practicing in industry, taking into consideration the materials offered in similar courses at other universities [1]. In 2000, the department further refined the course contents to ensure compliance with the ABET 2000 criteria, which stressed the need for assessment of the course based on the outcomes.

This paper highlights the important aspects of the course: 1. Course development based on alumni feedback and ABET criteria. 2. An instrumentation teaching rig that can be configured easily in *both* hardware and software to give a wide range of learning experience. 3. The outcomes of the course as viewed by practicing engineers and researchers.

COURSE PHILOSOPHY, COVERAGE AND FORMAT

The course learning objectives are:

1. To understand the principles of operation and limitations of common measuring instruments.
2. To model transducers and their operating conditions.
3. To design systems for the acquisition, analysis, and communication of data.
4. To gain awareness of the economical and societal aspects of instrumentation systems and of presentation of information.

The depth of coverage of each topic was decided on using the cognitive domain taxonomy [2] based on the department's ABET 2000 [3] performance objectives. As in most other instrumentation and data acquisition courses, students learn about transducers for pressure, flow, temperature, humidity, force, etc. They also build signal-conditioning circuits such as a strain gage signal conditioner with a Wheatstone bridge, operational amplifiers, and active filters. Other experiments include interfacing with global positioning systems (GPS) and various other sensors used in precision agriculture. Details of the course topics, including lecture notes and laboratory handouts, are linked to the class home page [4]. The topics can be grouped into

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three parts for the purpose of keeping up with the latest technology while maintaining the necessary mathematical basis of measurement science.

The first part comprises fundamental principles that have not changed for many decades and are not expected to change in the engineer's lifetime. This part includes statistics (precision, accuracy, review of probability distributions, regression analysis, etc.), system dynamics and modeling (first- and second-order system differential equations, responses in time and frequency domains, etc.), and basic electronic measurement (impedance, noise and filtering). This part is taught to provide a solid foundation for the rest of the course. The second part of the course teaches the principles of operation of transducers: motion, force, pressure, flow, and temperature. This part includes data acquisition with computers (analog-to-digital conversion, communication ports, and buses). This part evolves with technology. It is designed to equip students with the ability to learn and extrapolate their knowledge to specific instruments they will use in their professions. The third part teaches contemporary technologies in measurement and data acquisition applications. At the time this paper was written, for example, one week was spent studying the global positioning system (GPS), collecting field data, and processing the data. This part is updated frequently. It includes the concept of graphical programming, which will be explained later in this article.

This three-credit-hour course is conducted over 15 weeks; two hours of lectures and two hours of laboratory exercises each week. Two of the laboratory sessions are visits to companies to study their data acquisition systems. The web pages link to all lecture notes, homework assignments and solutions, practice problems, grades, etc. Electronic slides from the web pages are used to communicate concepts to the students quickly and efficiently. Even though all of the slides and lecture notes are available on the web pages, most of the mathematics is explained on the chalkboard and is left as blank spaces in the handouts distributed prior to each lecture. The reasons for not using projected slides for mathematical explanation are: 1) to allow students to take notes to reinforce the information they receive visually, and 2) to give students enough time to absorb the information. Some students absorb information better without taking notes. Such students have the option to refrain from taking notes in the classroom and to print out complete notes from the web pages. In any case, students do short calculations in class to reinforce the mathematics learned in the lecture.

Students in the course spend about half of the structured course time on hands-on exercises. Every lecture topic is reinforced with exercises in the laboratory session following the lectures. Graphical programming (explained below) is learned for three weeks in this course using the LabVIEW™ Hands-On Course manual [5], the same manual that is used by National Instruments in its training courses.

LABORATORY EQUIPMENT

In today's engineering curricula, the importance of learning basic electronics cannot be overstated. Some instrumentation courses even teach electronics as the main subject [6]. The first few laboratory exercises are building and testing elementary electronic circuits commonly required in instrumentation and data acquisition. For these exercises, the course provides common electronic tools and components such as multimeters, oscilloscopes, breadboards, data acquisition PCs, and function generators.

The transducers used by the students are those commonly used in industry, including pressure transducers, turbine and positive-displacement flow meters, rotameters, thermocouples, resistance temperature detectors, and thermistors. Other instruments in the laboratory include relative humidity transducers, programmable logic controllers (PLC), and differentially corrected global positioning systems (DGPS). Most of the transducers are mounted on a special instrumentation and data acquisition laboratory test stand. The test stand also has machinery hydraulic components such as flow control valves, needle valves, pressure relief valves, and a hydraulic accumulator. The laboratory has multiple units of such test stands. The test stand is described in detail in Brown and Sumali [7]. It was designed to combine the following features:

1. Modular: Different experiments can be performed on the test stand by rearranging quick-connect hose connections among the transducers.
2. Self-contained: The test stand has various instruments, power supply, PC, a pump to circulate water, heaters and heat exchangers to control the water temperature. The test stand can be used wherever there is an AC power outlet.
3. Portable: The test stand is mounted on lockable castors and fits most doors. Internet connection allows monitoring and control of the test stand from anywhere in the world.
4. Fully computerized: The PC on the test stand acquires, processes and displays data from the instruments and sends control commands to the instruments.

The Purdue Agricultural and Biological Engineering instrumentation test stand is shown in Fig. 1.

For three weeks, students learn National Instruments' LabVIEW™, which is the most widely used software for graphical programming in industry. With this program, students create their own 'virtual instruments', such as an oscilloscope with mouse-driven control switches and buttons on a PC screen. The same hardware used to build the

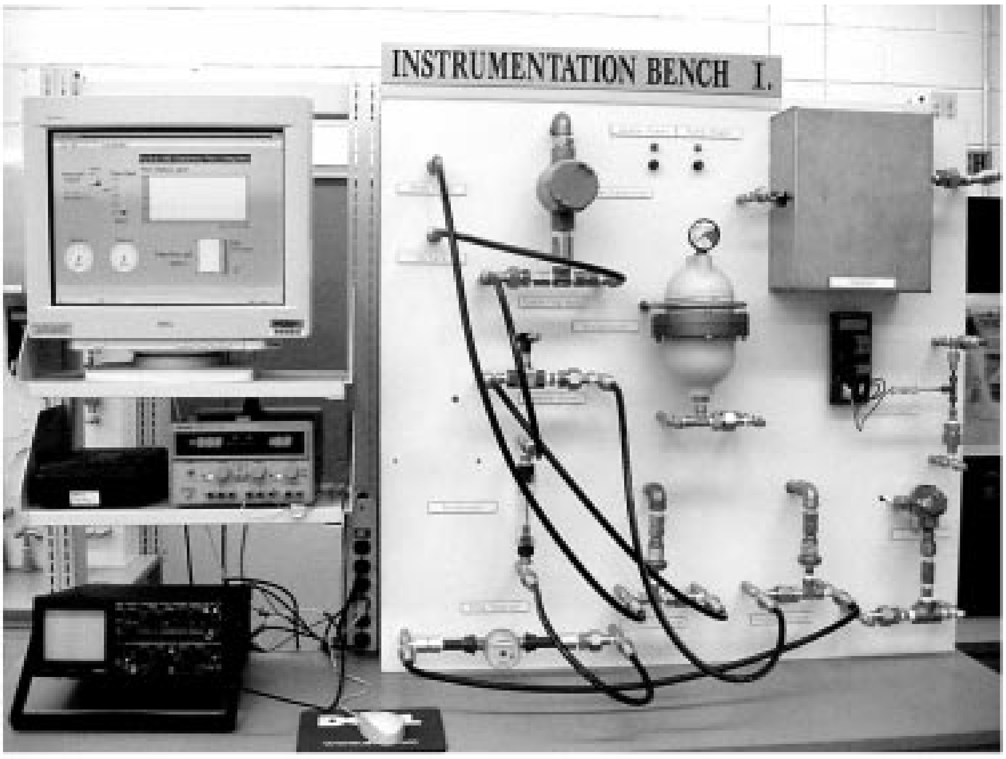

Fig. 1. Instrumentation and data acquisition laboratory test stand.

oscilloscope can be reprogrammed to function as a spectrum analyzer and other instruments. (Virtual Instrumentation was a novel technology in Agricultural Engineering education at the time this paper was written. It is no longer novel today. However, the spirit of this paragraph is to inspire course transformation of similar impact but with the technology that is novel in the reader's time.)

SAMPLE EXPERIMENTS

Laboratory experience in the class includes: building and dynamically testing electronic filters, operational amplifier circuits, installing hardware and software for data acquisition, building current transmission loops with transducers, calibrating pressure, flow and temperature transducers, determining the accuracy, precision, etc., of the transducers, determining dynamic parameters (time constants, natural frequency) of transducers, building communication links, and using GPS. The following sub-sections give specific examples of what students learn.

Strain gage signal conditioning

The course is designed so that most of the principles that are introduced are used later in studying further topics and applied in laboratory experiments. The strain gage signal conditioning experiment is an example of the above concept. This experiment teaches students how to apply their knowledge of load cells, Wheatstone bridge, operational amplifiers, active filters, calibration, and virtual instrumentation, to design and test a weighing scale that can be used in the real world. Figure 2 shows the schematic diagram, and Fig. 3 shows a photograph of the system. The object to be measured is placed or hung on the tip of the beam. The strains on the top and bottom of the beam alter the resistances of the strain gages, which are half of a Wheatstone bridge. The resulting voltage imbalance is amplified by an instrumentation amplifier circuit. An active low-pass filter suppresses high-frequency noise and further amplifies the signal. The output of the filter is sent to a data acquisition board in a PC. A virtual instrument on the PC displays the weight on the computer screen. The virtual instrument can also be put into calibration mode, where it obtains the calibration factor from voltage to weight by regression analysis, and removes the tare or other initial offset reading.

Given the specifications, students design the beam dimensions and the values of the resistors and capacitor, fabricate the beam in the shop, attach the strain gages, build the electronic circuit on a breadboard, and create the virtual instrument by programming the data acquisition system.

Flow measurement

In the flow measurement experiment, students:

1. hard-wire 4-20 mA current loops to transmit data from a turbine flow meter and two pressure transmitters;
2. investigate the quadratic relationship between pressure drop and flow rate;

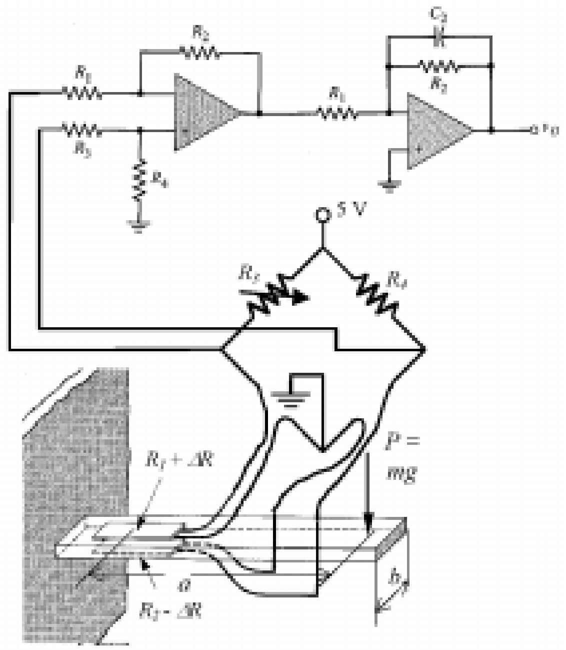

Fig. 2. Schematic diagram of strain transducer setup.

3. write a virtual instrument that integrates the flow rate with time to compute total volume flow;
4. compare the result of the integration with the reading from a positive-displacement flow totalizer;
5. acquire and process data from pressure transmitters, turbine flow meters, positive displacement flow totalizers, and rotameters; and
6. learn to characterize instruments in terms of calibration curves, resolution, precision, accuracy, etc.

The piping and instrumentation diagram (P and ID) [8] of the experiment setup is shown in Fig. 4, Fig. 5 shows the front panel of the virtual instrument, and Fig. 6 shows the diagram of the virtual instrument to illustrate the extent of the graphical programming task accomplished by the typical student in one week.

OUTCOME

The outcome of the course has been assessed using a variety of measures. Four years after it was started, the course has shown significant impacts within the department, at the university, on its graduates who practice in industry, and overseas.

Achievement of learning objectives

All graded course material was developed to measure the achievement of the learning objectives stated above. Therefore, the average class grade was a direct measure of the course outcome. The median grade in each year was B. Sample test and homework problems posted on the class website [4] give an idea of how that grade relates to students' expertise in instrumentation.

Course evaluations

At the end of the semester, students were reminded of the course objectives and were asked to evaluate the course. Therefore, the course evaluation is a measure of whether the course objectives are achieved. From the first time the course was offered in 1998 until 2001, students have evaluated the course under two different standard course evaluation methods implemented by Purdue University. The first standard was used in 1998 and 1999. The evaluation questions and student responses for 1998 and 1999 are shown in Table 1. The number of respondents was nine for both years. Shown in the table are median ratings on the scale of 1 (strongly disagree) to 5 (strongly agree). Only questions related to the outcomes of the course are listed.

Fig. 3. Load cell design experiment.

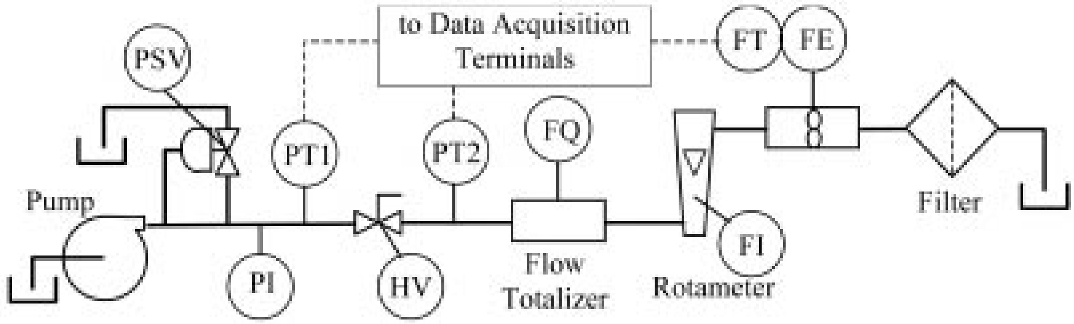

Fig. 4. Piping and instrumentation diagram (P&ID) of flow measurement setup.

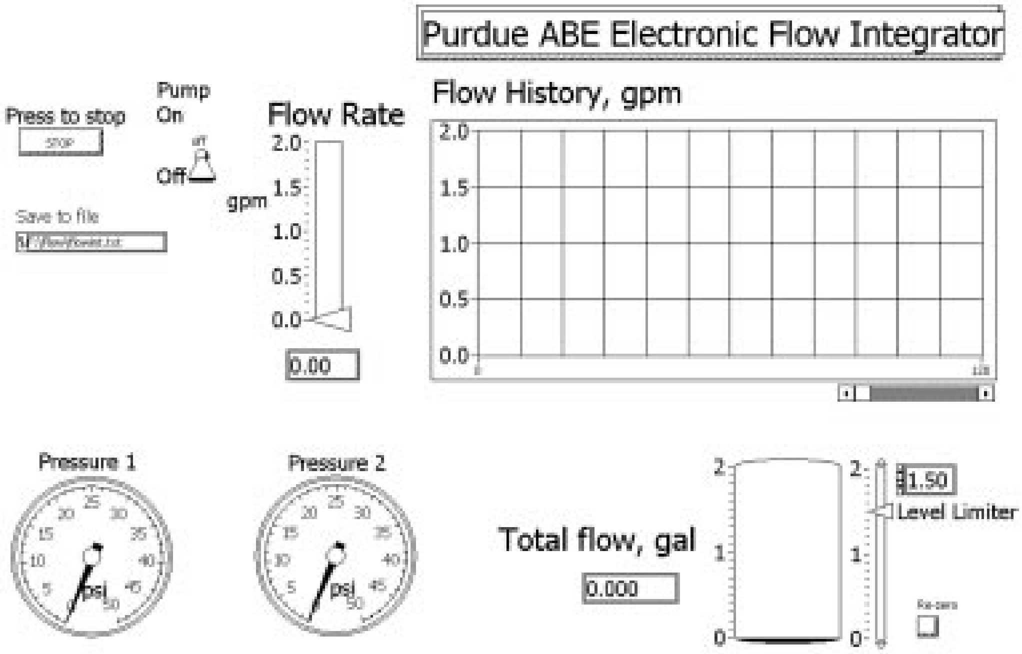

Fig. 5. Front panel of flow measurement virtual instrument.

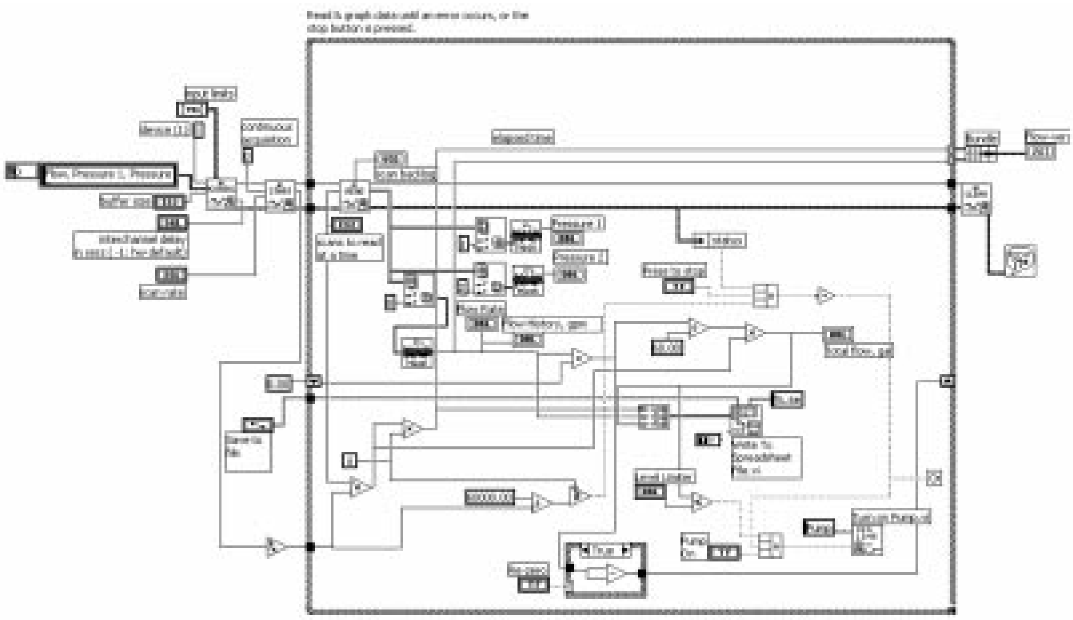

Fig. 6. Diagram of flow measurement virtual instrument written by a student.

Table 1. Student responses to course evaluation questions—1998 and 1999

No.	Statement	1998	1999
1	This course supplies me with an effective range of challenges	4.2	4.3
2	This course has effectively challenged me to think	4.1	4.1
3	My background is sufficient to enable me to use course materials	4.3	4.2
4	The course content is consistent with my prior expectations	3.6	4.0
5	This course material is pertinent to my professional training	4.1	4.3
6	Complexity and length of course assignments are reasonable	4.0	4.1
7	The teaching strategy used in this course is appropriate	4.1	4.0
8	Course assignments are interesting and stimulating	3.9	4.0
9	Overall, this course is among the best I have ever taken	3.8	4.1

The evaluation questions and student responses for 2000 and 2001 are shown in Table 2. The number of respondents was 16 in 2000 and 15 in 2001. The numbers in the table are median ratings on the scale of 1 (very poor) to 5 (excellent), unless otherwise noted.

Impact on department's research

The ABE department at Purdue University has computerized its data acquisition for at least three decades. However, graphical programming has been used in the department's data acquisition for only a few years. Campus-wide, students use virtual instruments to acquire data in their laboratory experiments in courses such as physics and many engineering courses. However, few users of graphical programs were able to write their own virtual instruments. This course has been taken by students from several departments at Purdue to learn graphical programming and computerized data acquisition. The impact of this course on research in the ABE department is illustrated in the examples below.

Created by the department's Odor Control Research group, the Purdue ABE mobile instrumentation laboratory is a large trailer equipped with a computerized data acquisition system and numerous sensors for odoriferous gases. An example of virtual instruments used with that mobile laboratory is shown in Fig. 7. In this example, the virtual instrument monitors important variables in a laying hen house on a chicken farm, such as various temperatures, relative humidity, pressures, concentrations of gasses, wind speed and direction, fan conditions, etc. The variables are updated every 10 seconds, are animated on the web page, and are accessible worldwide via the internet [9]. The instrumentation was built by Purdue ABE graduate researchers, who had learned to write virtual instruments in the course.

Another example where graduates from the course have created virtual instruments for use in their research in the department is the university's Grain Storage laboratory [10]. One of the test setups is a grain storage bin instrumented with numerous transducers. The grain temperature in the bin is monitored by temperature sensors in five different elevation levels. Each level has five temperature sensors—one at the center and one each in the north, east, south and west in the periphery. Similarly, other transducers monitor moisture content, CO_2 concentrations, gas flow, relative humidity of the air in the bin, temperature and relative humidity of the outside air, insect population density, etc. All of these variables are monitored and logged by a virtual instrument, which also controls the force flow of air, a gas burner, control valves, louver dampers, etc. A small part of the virtual instrument measures the speed and direction of the wind, as shown in Fig. 8. One of the grain bins operates with refrigerated air. The instrumentation for the refrigerated-air grain bin is more involved than that of the grain bins mentioned earlier.

Impact on graduates in industry

The projects presented here are specifically projects in instrumentation, data acquisition, and virtual instruments, which the students did not learn before the course was created. The students

Table 2. Student assessments of the course—2000 and 2001

No.	Criteria	2000	2001
1	Average hours/week I spent outside of class	3.1	4.3
2	Effort I put forth to learn the material in this course	4.2	4.0
3	My class attendance was:	4.8	5.0
4	The course appears to be well organized	4.1	4.4
5	The course content is interesting to me	4.8	4.6
6	I developed skills needed by professionals in my field	4.7	4.4
7	Handouts contribute to my understanding of the course	4.7	4.8
8	Complexity and length of course assignments are reasonable	4.2	4.6
9	Laboratory experiences assist me in learning concepts	4.2	4.6
10	Class projects are related to course goals and objectives	4.3	4.3
11	Overall, I would rate this course as:	4.6	4.4

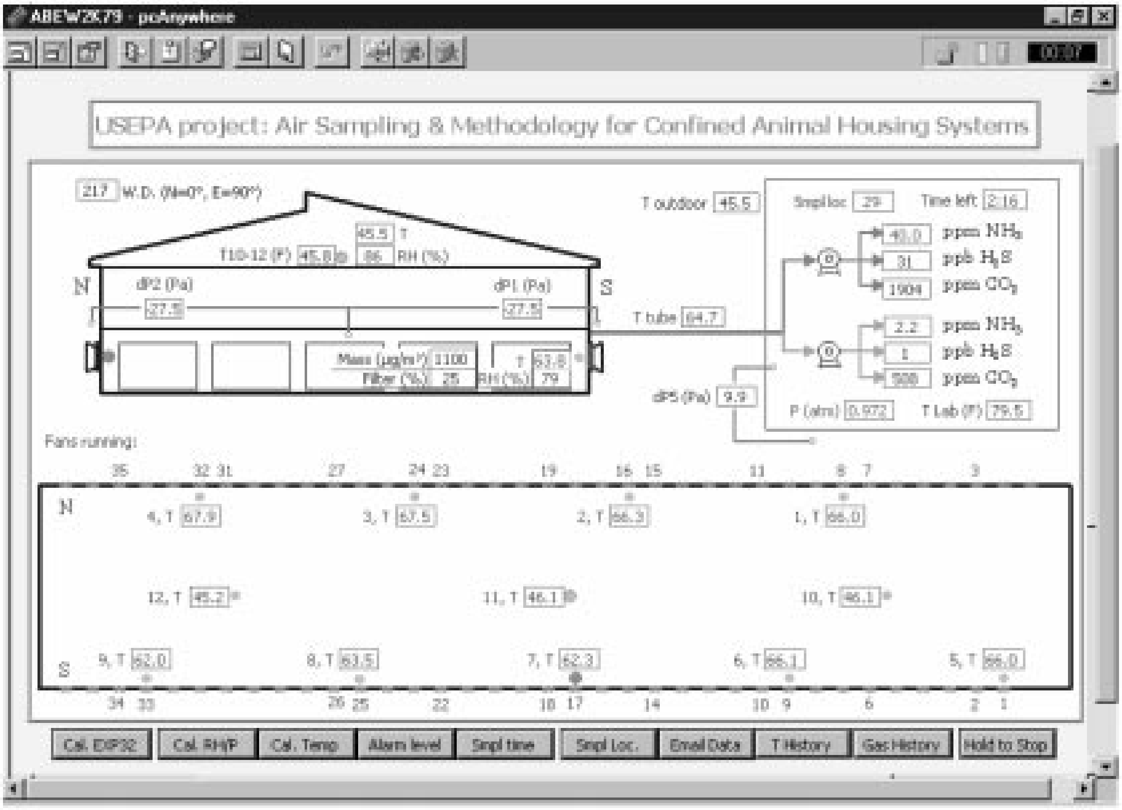

Fig. 7. An internet-based virtual instrument of Purdue ABE Odor Control mobile laboratory.

did not take training courses in the subject after completing the course discussed here.

A student in the class was a full-time engineer at a gear manufacturing company. He uses the graphical programming that he learned from the course to design and configure a data acquisition system for quality control of gears. This virtual instrument is for a static torque cycle test stand. A torque is applied to the gearbox via a generated waveform signal in the virtual instrument. This waveform directs a hydraulic servo valve that is connected to a hydraulic cylinder that applies the torque (via a torque arm) to the gearbox. Feedback is obtained through a load cell mounted

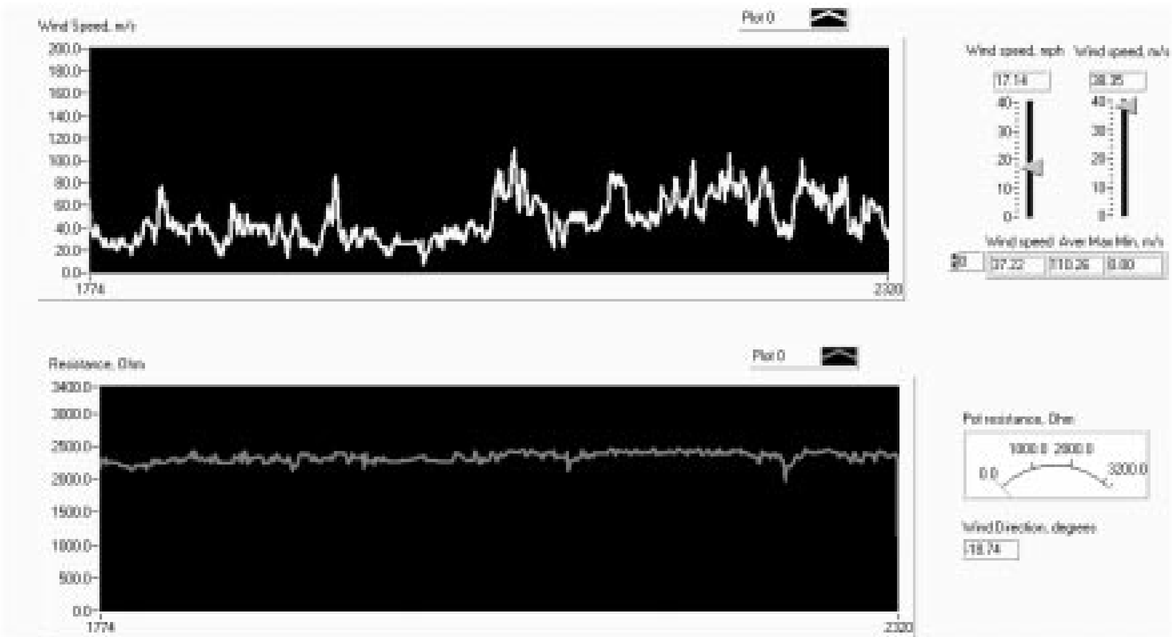

Fig. 8. A virtual instrument from Purdue ABE Grain Storage laboratory.

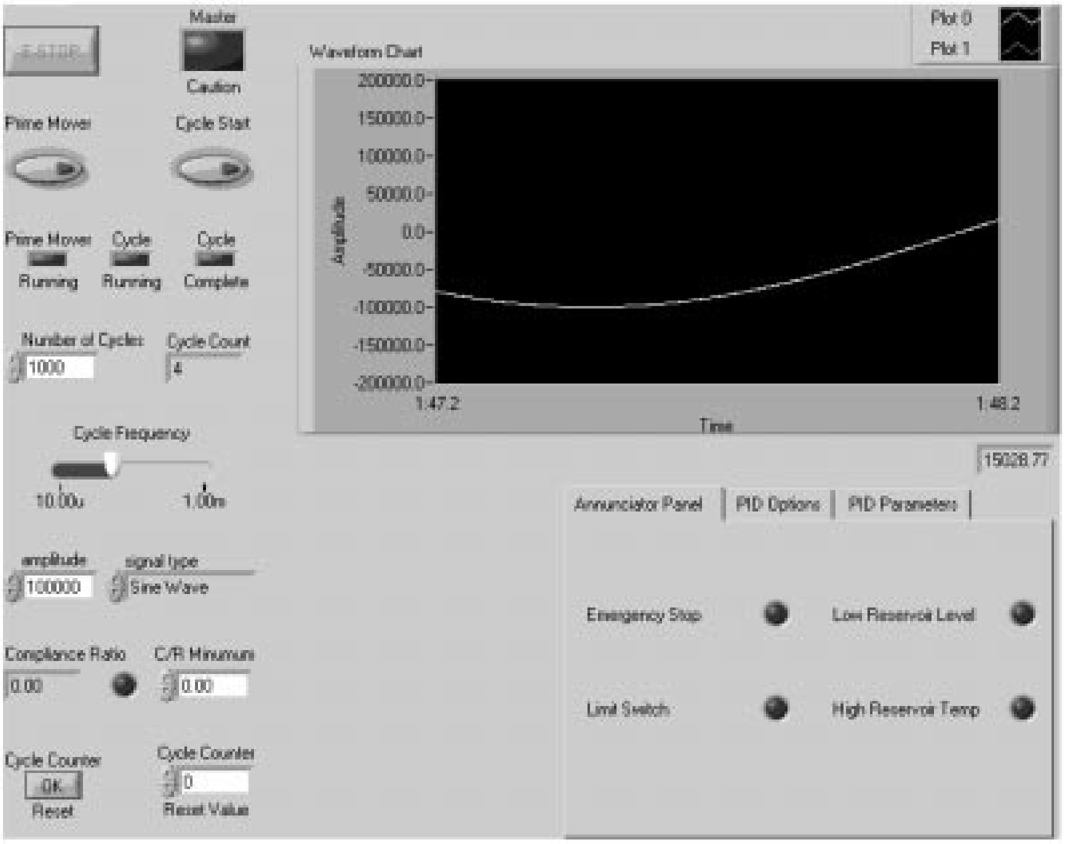

Fig. 9. A virtual instrument written by a graduate from the course in industry.

between the cylinder and the torque arm. This virtual instrument has a PID controller embedded within it [11]. The virtual instrument panel is shown in Fig. 9.

Another example where a graduate from the course uses the skills he learned from the course is the virtual instrument used to control a test station called 'Seat Power Track Stability Test Stand.' It is used by the Mechanism Department at Johnson Controls to test and study seat power tracks of automobiles. A seat power track is the mechanism below the seat that automatically moves the seat in forward or up-and-down directions. There are two-way (forward/backward) and six-way (fore/aft, front tilt up/down, and rear tilt up/down) power tracks. Figure 10 illustrates the

Fig. 10. Virtual instrument for controlling a seat power track stability test stand. Courtesy of Johnson Controls, Detroit, MI.

data acquisition screen a user first arrives at. It shows the various features of the test setup, which include the measurement of 'stability', torque, 'recliner stability', and speed of operation. Stability is a term used in the power track business to measure the deflection of the track in the horizontal and vertical direction when the seat is pulled and pushed in the horizontal direction. This term is used to quantify a customer's rocking in the seat. The deflection is critical to the power tracks, as a tight track is a good track and any looseness/chuck in the seat can be felt when the car suddenly decelerates. The deflection is measured using LVDTs in two horizontal positions and four vertical positions. Recliner stability is stability applied to the recliner of the seat. Speed of operation indicates how long the track takes to move a specified distance. All tracks have a minimum speed requirement that they need to meet. On the setup, it is run using a six-graph screen, which displays speed in mm/s for all horizontal and vertical directions. Figure 11 shows an example of what the VI operator sees when conducting the experiment [12].

Impact on curricula

After being taught for two years on an experimental basis, the course was approved by Purdue's Schools of Agriculture to be taught with a permanent course number. A year later, the course gained approval from Purdue Schools of Engineering for adoption into the engineering curricula.

The overseas impact of the course is shown by the fact that the course was adopted into the curriculum of the Agricultural Engineering Department at the Federal University of Viçosa (UFV) in the state of Minas Gerais, Brazil [13]. A UFV professor learned about the course, obtained funding for laboratory instruments, and arranged for the setup of the course at UFV. The author was invited to teach the course at UFV in May and June 2000. Many of the lecture topics and materials were readily transplantable to the educational objectives of UFV [14]. A significant difference may be that the department at UFV is a combination of Agricultural Engineering and Agricultural Mechanization (*Mecanização Agrícola* in Portuguese), which emphasizes more practical skills and less calculus than the curricula of most U.S. engineering departments. This difference is addressed by skipping some calculus in such topics as first- and second-order dynamics, error propagation, electronic filters, etc., and replacing it with more lab exercises in the installation of strain gages, data acquisition hardware, etc.

Acknowledgment from students, faculty and professional organizations

One graduate from the course was selected to be a recipient of the highest graduate-level scholarship from the Instrument Society of America (ISA) Educational Foundation in 2001 [15]. ISA specifies that 'Scholarships are awarded to graduate and undergraduate students who demonstrate outstanding potential for long-range contribution to the fields of instrumentation, systems, and automation' [16]. From a worldwide pool of candidates, two students were selected for that level of scholarship in 2001.

Other evidence of the recognition of the course by Purdue students and faculty is that the instruc-

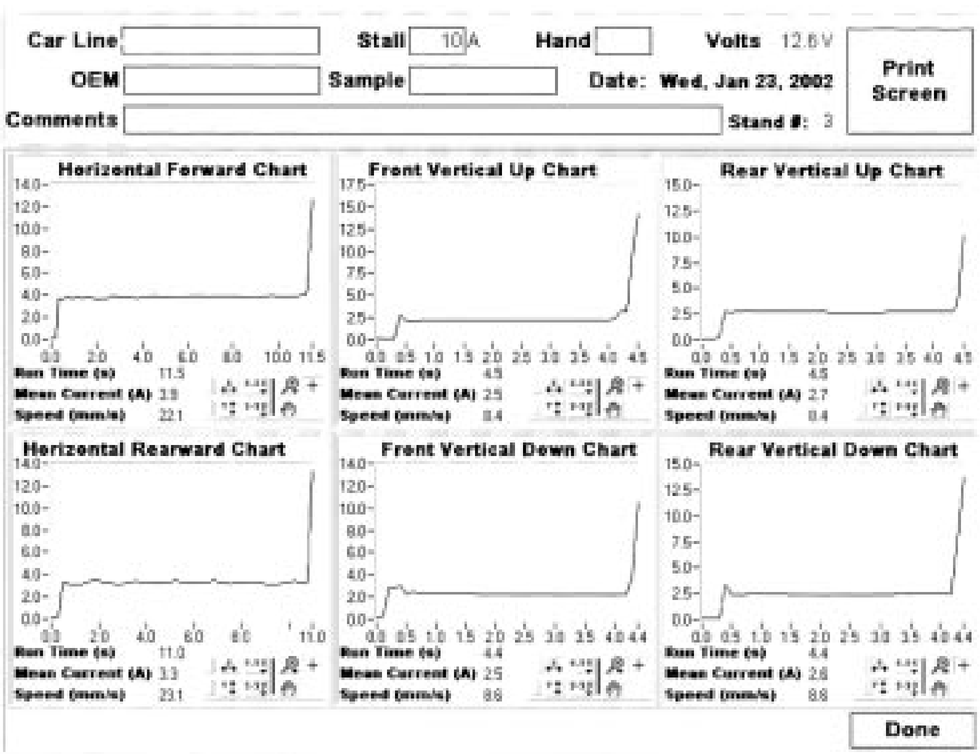

Fig. 11. Results from a seat power track stability test. Courtesy of Johnson Controls, Detroit, MI.

tor was selected as the outstanding engineering teacher in the department two years in a row. A committee of students and faculty from the Purdue Schools of Engineering later awarded him the A. A. Potter Outstanding Undergraduate Teaching Award. Even though he was teaching two other courses, the Instrumentation and Data Acquisition course appeared to be a strong contributor to his selection as the recipient of the awards.

CONCLUSIONS

Alumni feedback has resulted in the establishment of a course in instrumentation and data acquisition, a skill which is often required in industry today. The laboratory teaching rig can be configured in both hardware and software to perform a wide range of experiments. This teaching technology was novel and transformational. Multiple metrics showed that the objectives of the course were generally achieved.

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