

An Instrumentation and Data Acquisition Course at Purdue University

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Abstract

The course teaches measurements of variables common in industry, signal conditioning, data acquisition using computers, data processing, and transmission and communication of measurement results. Graphical programming is used by students to write programs for the acquisition, processing, and presentation of data.

The instrumentation laboratory test stands have 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 have applied the skills gained in the course to research and industrial uses. The course has helped one of its students win an international scholarship. Started at Purdue University, the course has been taught at, and is in the process of being adopted by a university in Brazil.

Introduction

In 1996, the agricultural and Biological Engineering (ABE) Department at Purdue University conducted one of its periodic curriculum reviews. In that review, its alumni in engineering and management professions expressed that ABE graduates needed better skills in measurement instrumentation and data acquisition. As a response to the alumni feedback, and to the emerging field of precision agriculture, 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 universities¹. In 2000, the Department further refined the course contents to ensure compliance with the ABET 2000 criteria, which stressed an assessment of the course based on the outcomes.

This paper highlights two important aspects of the course: the outcomes of the course as viewed by practicing engineers and researchers, and the means to achieve those outcomes, particularly the learning methodology and the laboratory equipment. Additionally, the paper discusses a novel concept in learning instrumentation, namely, the hands-on learning of virtual instruments

through graphical programming. It is hoped that this documentation of the course might serve as a model for teaching and learning measurement and data acquisition.

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 economical and social aspects of instrumentation systems and of presentation of information.

The depth of coverage of each topic was selected using the cognitive domain taxonomy² based on the Department's ABET 2000³ performance objectives. Like 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 page⁴. The topics can be grouped into three parts for the purpose of keeping up with the latest technology commonly used in industry.

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 (e.g., 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), 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 transducers' principles of operations: motion, force, pressure, flow, and temperature. This part includes data acquisition with computers (analog-to-digital conversion, communication ports, 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. Time limits the coverage to representative principles.

The third part teaches contemporary technologies in measurement and data acquisition applications. For example, one week is spent studying the global positioning system (GPS), collecting field data, and processing the data. This part is updated frequently. This part includes the concept of graphical programming, which will be explained later in this article.

This three-credit-hour course is conducted in 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. 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 use the notes from the web pages. In either 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 class time on hands-on exercises. Every lecture topic is re-emphasized with laboratory exercise in the session immediately following the lectures. Graphical programming (explained in a later section) is learned for three weeks in this course using LabVIEW™ Hands-On Course manual⁵, the same manual that is used by the software company, 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 subject⁶. 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.

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. Currently, the laboratory has three such test stands. The test stand is described in detail by Brown and Sumali⁷. The test stand 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 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 Figure 1.

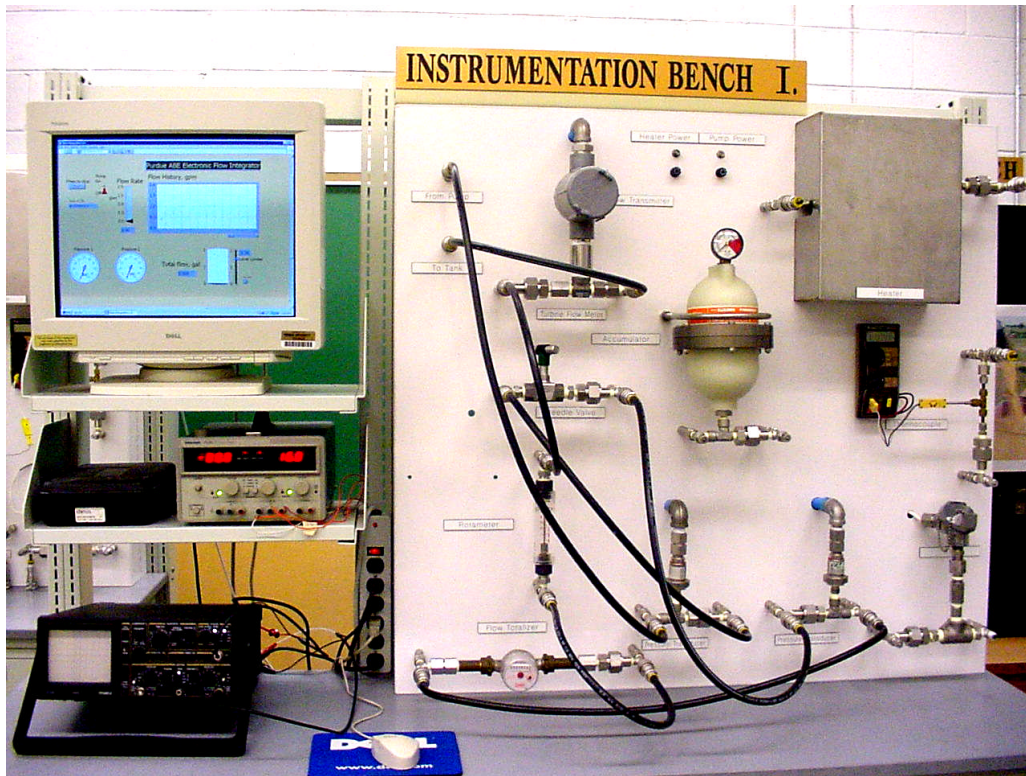


Figure 1 Instrumentation and Data Acquisition Laboratory Test Stand.

Graphical Programming

For three weeks, students follow hands-on instruction of National Instruments' LabVIEW™, which is the most widely used software for graphical programming in industry. With this program, students create their own “virtual instruments”. An example of a virtual instrument is as an oscilloscope with mouse-driven control switches and buttons on a PC screen. Students create this oscilloscope in the class. With a data acquisition board, the oscilloscope functions in the same manner as a “real” oscilloscope. However, the same hardware used to build the oscilloscope can be reprogrammed to function as a spectrum analyzer and other instruments. In essence, graphical programming converts the PC into various instruments designed by the programmer. The advantage of virtual instruments over “hard-wired” instruments is that the former are much more versatile and economical.

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 examples of what students learn specifically.

Strain gage signal conditioning

The course is designed so that most of the principles that are introduced are later used in studying further topics and applied in laboratory experiments. The strain gage signal conditioning experiment gives a typical example of the foregoing statement. This experiment allows students 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 Figure 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.

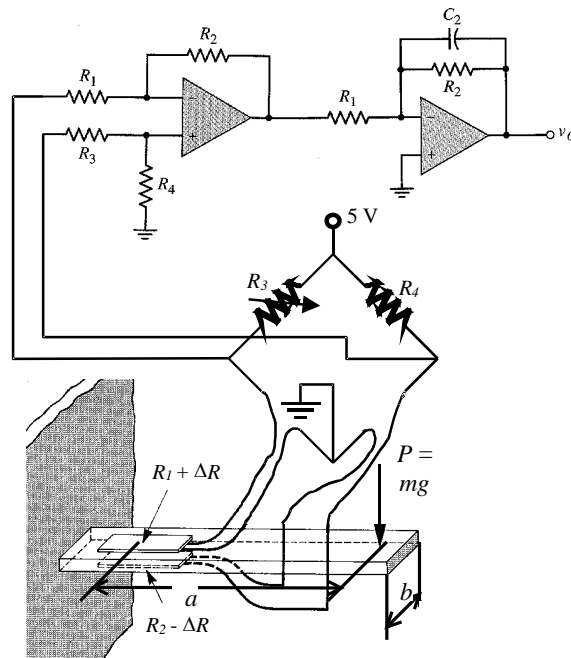


Figure 2 Schematic Diagram of Strain Transducer Setup.



Figure 3 Load Cell Design Experiment.

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.
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. Learn to acquire and process data from pressure transmitters, turbine flow meters, positive displacement flow totalizers, and rotameters. These characteristics include precision, accuracy,

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

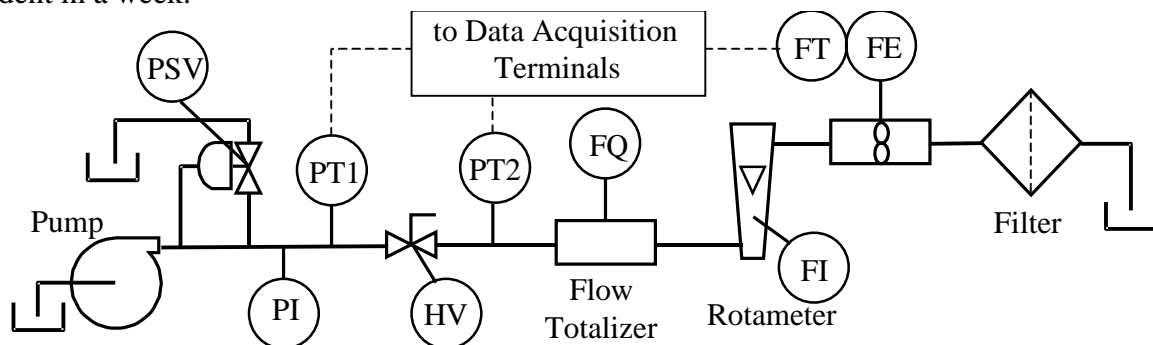


Figure 4 Piping and Instrumentation Diagram (P&ID) of Flow Measurement Setup.

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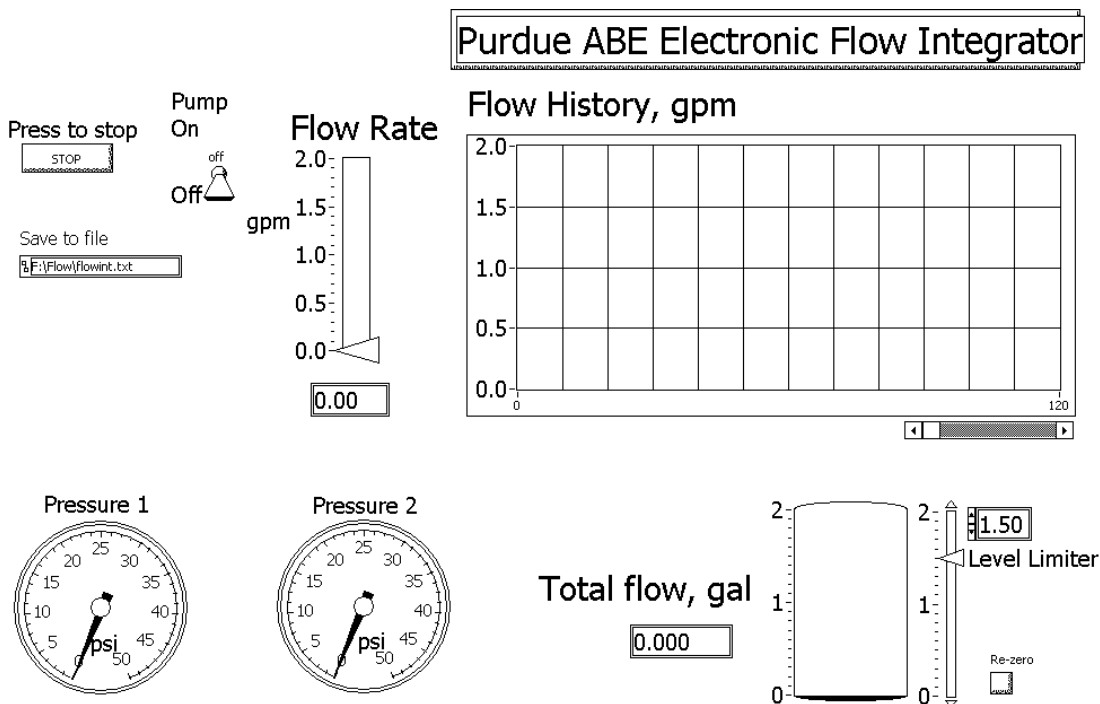


Figure 5 Front Panel of Flow Measurement Virtual Instrument.

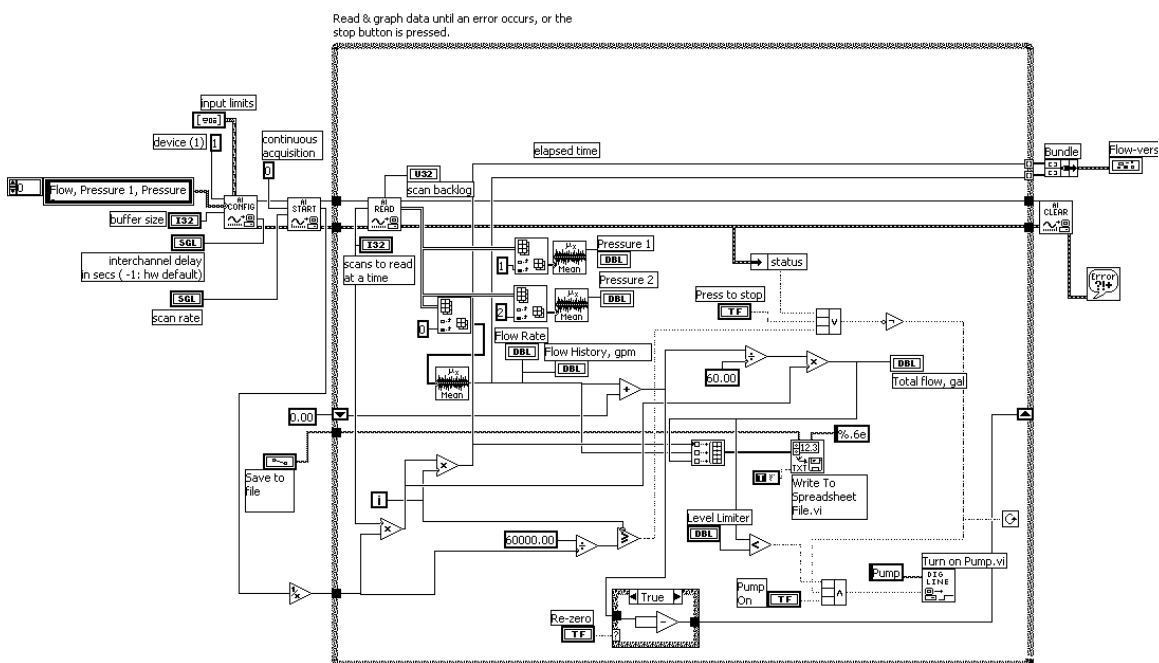


Figure 6 Diagram of Flow Measurement Virtual Instrument Written by a Student.

Outcomes

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

1. Course Evaluations

Part of the outcome of a course is how students think about various aspects of the course. From the first time the course was offered in 1998 until 2001, students have evaluated the course under two different standard course evaluation methods. 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 numbers of respondents were 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.

Table 1 Student Responses to Course Evaluation Questions – 1998 and 1999

No.	Question	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 1. The numbers of respondents were 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.

2. 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 such courses as Physics and many engineering courses. However, few users of graphical programs are 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 with the examples below.

Table 2 Student Assessments of Course – 2000 and 2001

No.	Criteria	2000	2001
1	Average hours/week I spent outside of class ¹	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

¹“1” means less than 2.00, “2” means 2.00-2.49, “3” means 2.50-2.99, “4” means 3.00-3.49, “5” means greater than 3.50.

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 Figure 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, animated on the web page, and is accessible worldwide via the Internet⁹. The instrumentation was built by Purdue ABE graduate researchers, who learned to write virtual instruments in the course.

Another example where graduates from the course create virtual instruments for use in their research in the Department is the University’s Grain-Storage laboratory¹⁰. 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 contents, CO₂ 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 those variables are monitored and logged by a virtual instrument, which also controls the force flow of air, a gas burner, control valves, louvre dampers, etc. A small part of the virtual instrument measures the speed and direction of the wind, as shown in Figure 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.

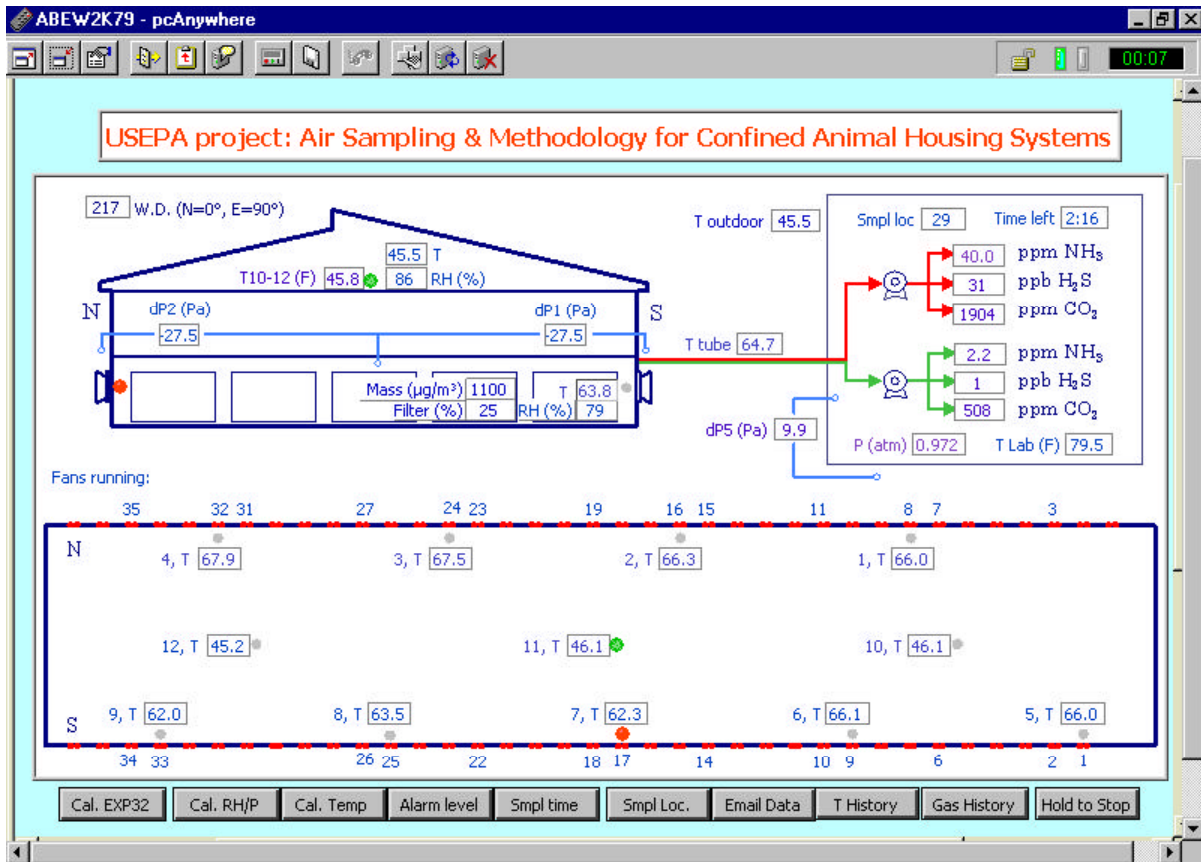


Figure 7 An Internet-Based Virtual Instrument of Purdue ABE Odor Control Mobile Laboratory.

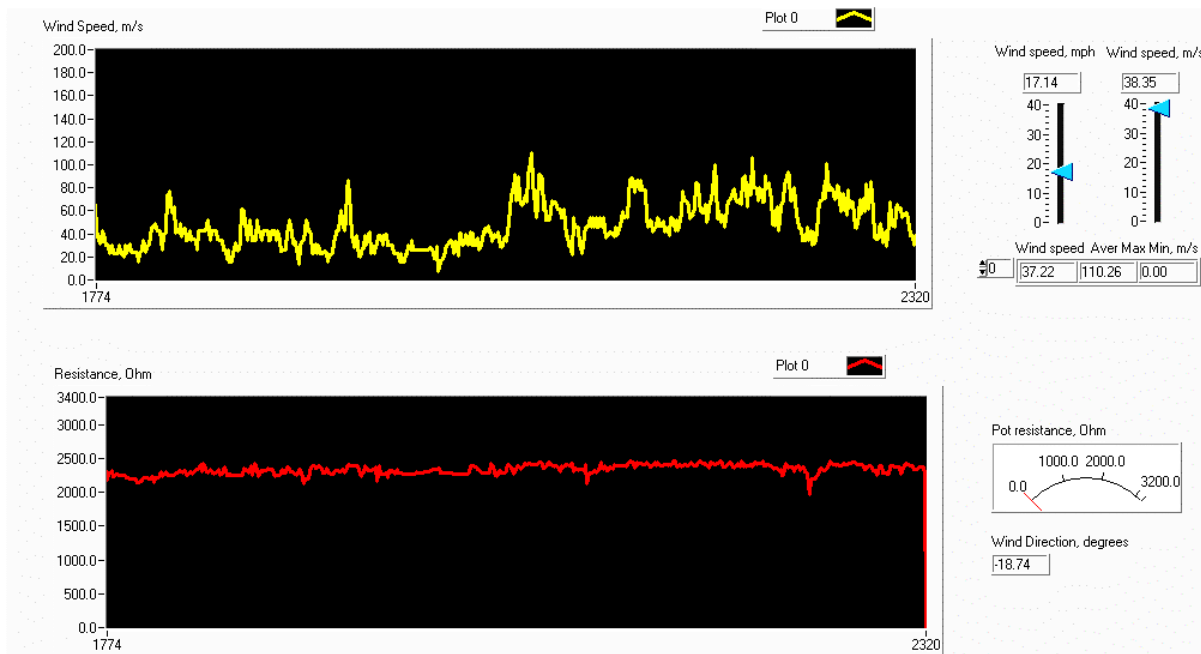


Figure 8 A Virtual Instrument from Purdue ABE Grain Storage Laboratory.

3. Impact on Graduates in Industry

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 done through a load cell mounted between the cylinder and the torque arm. This virtual instrument has a PID controller embedded within¹¹. The virtual instrument panel is shown in Figure 9.

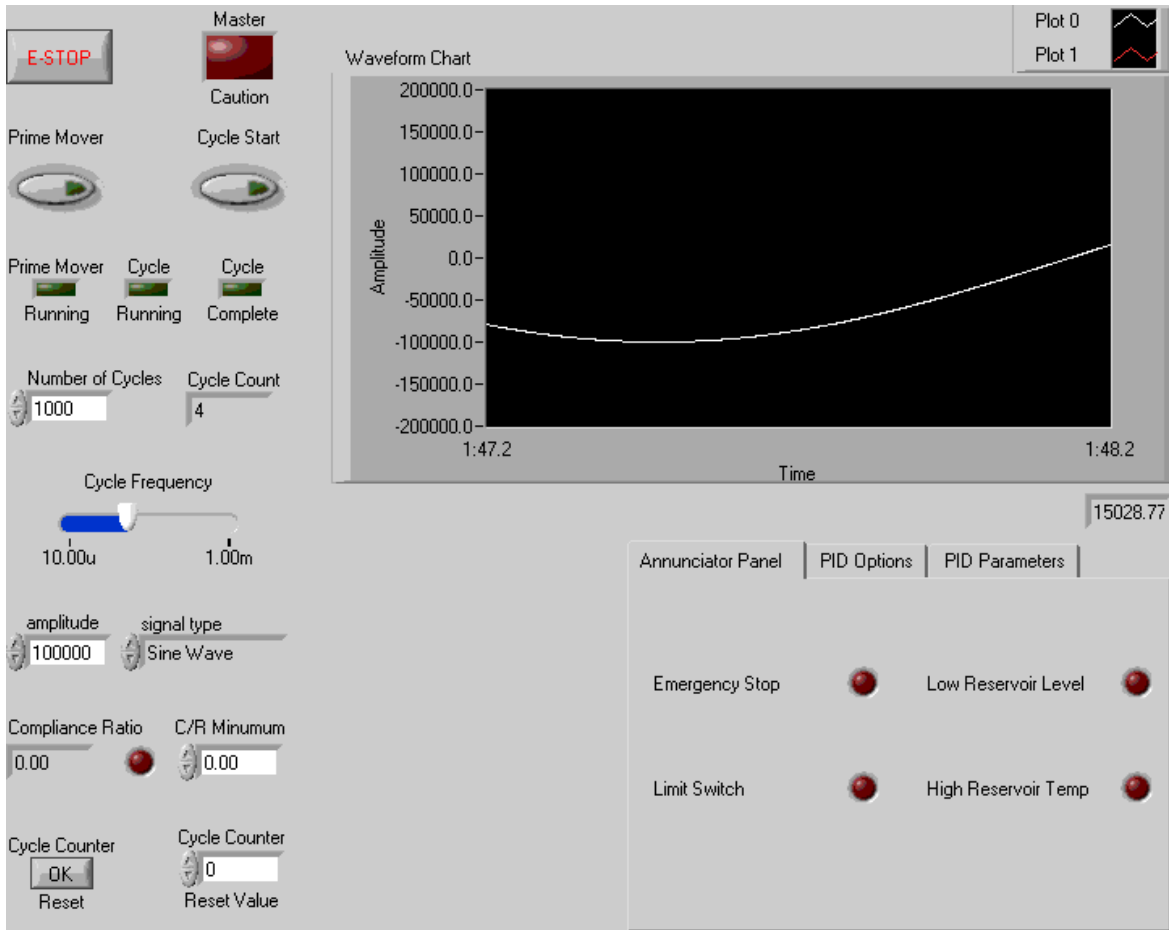


Figure 9 A Virtual Instrument Written by a Graduate from the Course in Industry.

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 Control 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-an-down directions. There are 2-way (forward/backward) and 6 way (fore/aft, front tilt up/down, and rear tilt up/down) power tracks. Figure 10 illustrates the 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. It is somewhat akin to a customer 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 tracks speed in mm/s for all horizontal and vertical directions. Figure 11 shows an example of what the VI operator sees when conducting the experiment¹².

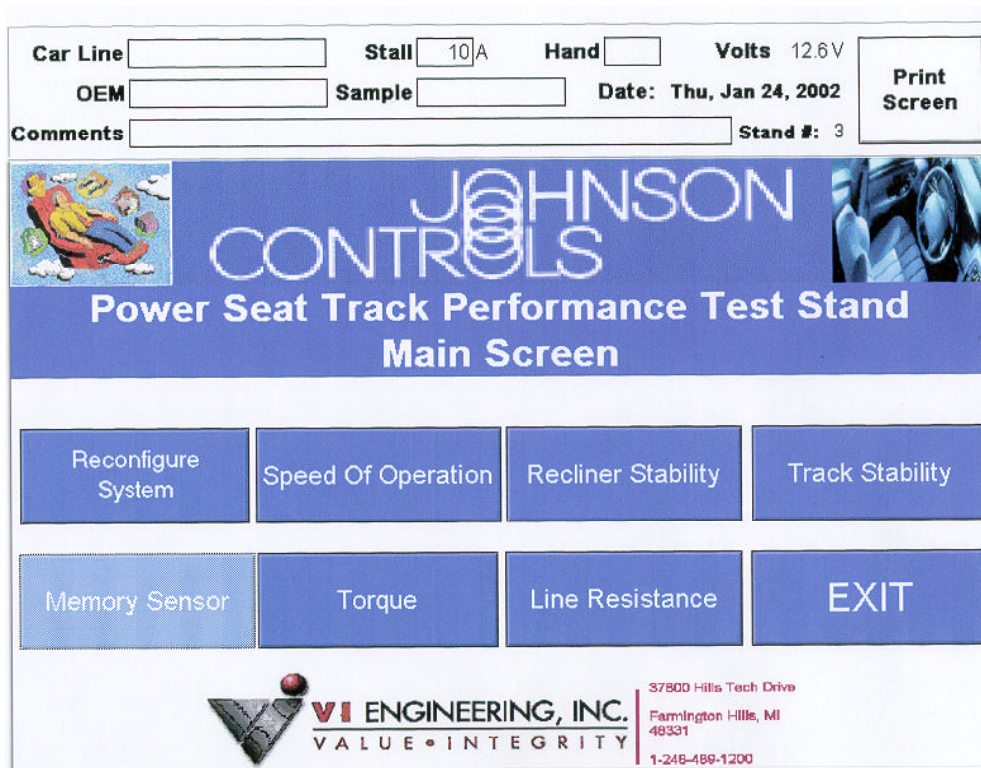


Figure 10 Virtual Instrument for Controlling a Seat Power Track Stability Test Stand. Courtesy of Johnson Control, Detroit, MI.

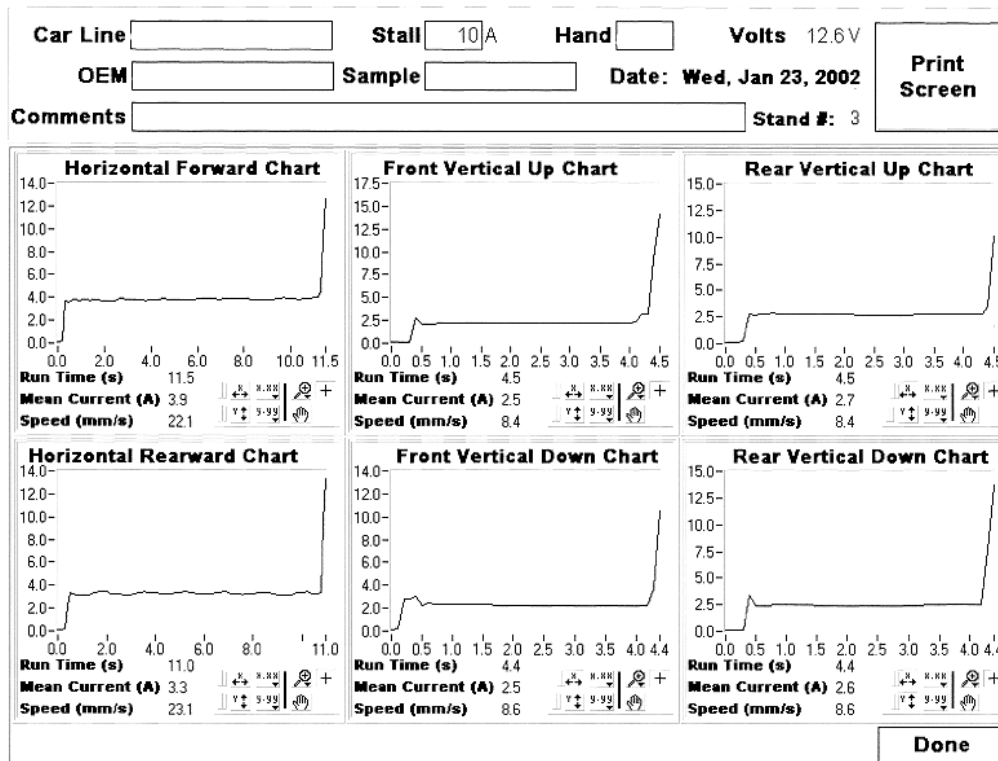


Figure 11 Results from a Seat Power Track Stability Test. Courtesy of Johnson Control, Detroit, MI.

4. Impact on Curricula

After being taught for two years on an experimental basis, the course has been approved by Purdue's School of Agriculture to be taught with a permanent course number. The course is being reviewed by Purdue Schools of Engineering for adoption into the engineering curricula.

Another impact of the course is shown by the fact that the course is being adopted into the curriculum of the Agricultural Engineering Department at the Federal University of Viçosa (UFV) in the state of Minas Gerais, Brazil. A UFV professor learned about the course, obtained funding for laboratory instruments, and arranged for the starting of the course at UFV. The author was to teach the course at UFV in May and June 2000. Many of the lecture topics and materials are readily transplantable to the educational objectives of UFV¹³. A significant difference may be that the department at UFV is equivalent to what is known in the U.S.A. as 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.

Acknowledgement 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 2001¹⁴. 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.”¹⁵ From a worldwide pool of candidates, two students were selected for that level of scholarship in 2001.

Other evidence of the acceptance of the course by Purdue students and faculty is that the instructor was selected to be the outstanding engineering teacher in the Department two years in a row. By a committee of students and faculty from the Purdue Schools of Engineering, he was also awarded the A. A. Potter Outstanding Undergraduate Teaching Award. Even though he teaches 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 and Future Plans

After being taught for a few years, the course is planned to be a required course in the curriculum of Purdue University’s ABE Department. Two major issues related to requiring the course are as follows. First, building up the laboratory equipment may require a few years’ funding accumulation with careful planning. For example, to ensure effective learning the course is conducted so that each student uses one PC with data acquisition hardware and software, a data accessory box, and a hands-on course kit for learning data acquisition and graphical programming. Each team of 2 or 3 students use one instrumentation test stand as described above. The Department wants to keep its current practice of having faculty members instead of teaching assistants to run undergraduate laboratories. Running multiple laboratory sections require significant faculty resource. As a result, class enrollment is currently capped to 18 students. For a course to be a required course in the Department, enrollment must not be capped.

Second, the engineering curricula currently leave little flexibility for changes. The engineering programs in the ABE Department must satisfy requirements from both the Schools of Engineering (for ABET accreditation) and the School of Agriculture (which funds the Department). To better prepare students for challenges in the increasingly complicated social and global challenges, both schools require increasing numbers of different requirements such as communication, international understanding, and economics, in addition to humanities and social sciences. The total required credit hours must be kept under a reasonable number (for example, 132 in some programs) so that students can normally complete the BS program in four years. Requiring a new course almost necessarily means removing another course from the program requirement. That means rearranging much of the curricula.

Acknowledgment

The author is grateful to the Purdue School of Agriculture for funding the course. He also would like to thank the Odor Research group in Purdue ABE Department, the Grain Storage Research group in the Department, Fairfield Manufacturing Company in Lafayette, IN, and Johnson Controls in Detroit, MI, for providing examples of real-world applications of the knowledge gained by former students in the class.

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Biography

Hartono Sumali obtained his Ph.D. in Mechanical Engineering from Virginia Tech in 1997, and has since been an assistant professor in Purdue University's Agricultural and Biological Engineering (ABE) Department. From 1987 to 1989 he was an instrumentation engineer for McDermott Inc., a company that builds offshore oil platforms. He has also worked for Caterpillar Inc. and the U.S. Navy. He has received several teaching awards from Purdue University and SAE International.