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Computer-Aided Physical Experimentation for Instrumentation and Measurements Classes in an Undergraduate Mechanical Engineering Program

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Abstract

The goal of this unique laboratory approach was to increase student interest in the subject, to increase the students’ learning efficiency, and to allow the students to apply their own creativity and hands-on problem solving skills. This approach, which uses unique experiments and open-ended projects, gives students the opportunity to stretch their creative limits by formulating and investigating realistic, inventive, and complex problems. This approach not only increases student’s enthusiasm, but it is also more closely aligns classroom topics with contemporary standard industrial environments. Furthermore, it lowers the cost of laboratory instruction by minimizing the amount of hardware that is used.

This paper reports the results of the development and implementation of hands-on laboratory experiments in a newly developed laboratory for a two-semester undergraduate course in Instrumentation and Measurements in Mechanical Engineering. The course, designed for the undergraduate junior level, was a two-semester course for a total of four credits, and it took place in conjunction with a one-hour classroom lecture in mechanical engineering. A modified version of this approach, however, can easily be used at all levels of the mechanical engineering curriculum. An important component to the process involves the utilization of a two-semester long, open-ended project (OEP) that required the students to come up with creative approaches to problem solving. Over the course of the year, a full-cycle learning experience took place. After acquiring the necessary minimum knowledge, the students began their OEP by developing an initial idea. They then went on to design and construct a working prototype (that included both system and measurement sensors on prototyping boards), and concluded the project by conducting a feasibility study by writing a report and delivering a class presentation. Because the ELVIS system has been used primarily as an instructional tool in electrical engineering laboratories, an extensive process that adapted it to the needs of mechanical engineering was implemented. This included the development of completely new experiments that involved newly-designed hardware and instructions that were all developed and built in-house with student participation.

Introduction

In the undergraduate teaching process, both instructors and students often get bored solving simple textbook problems that have limited connections to the real world and require little, if any, imaginative thinking to solve. To increase student interest, creativity, hands-on experience, and
problem-solving skills, a unique approach utilizing open-ended projects has been developed that encourage students to reach their creative limits. This approach, which formulates and investigates realistic, inventive, and complex problems, not only helps increase student enthusiasm, but also more closely aligns classroom topics with contemporary standards in industrial environments.

Although it can be useful to use theoretical and computational tools (including virtual tools) in the classroom to teach engineering processes, the superiority of using experimental approaches is obvious. Experiments are the only possible way to prove a hypothesis and make it a theory. Consequently, mechanical engineering students need to be equipped with hands-on experience in experimentation, instrumentation and measurements. This involves conducting physical experiments concerning what measurements to use, how to develop a feasibility study program, how to conduct computer-based data acquisition and analysis processes, how to validate experimental data for both deterministic and random processes, how to design experiments, and how to disseminate results. There are, however, many obstacles that must be overcome in order for this type of process to be successfully implemented. The most common obstacle is the financial burden of the required laboratory and a tremendous increase in the instructor’s teaching load; neither of these obstacles are recognized by current structures. These obstacles often force engineering educators to make compromises which replace laboratory experiments with virtual experiments and computer or black board exercises.

One way to reduce some of this burden is through the implementation of miniature mechanical systems with prototyping sensors and measurement systems as a part of the laboratory class experiments. The student can use a prototyping board to construct sensors and electronic transducers, which also allows the student to get a better understanding of measurement systems. In order to do this, however, the students need additional interdisciplinary knowledge that can then be implemented during the lab experiments. Thus, the first part of the class should address the development of sensors, measurement systems, experimentation, and data analysis. An inexpensive, computer-aided experimentation system like NI ELVIS makes this process even more appealing in today’s “lean” approach to engineering education. The second part of the class should utilize statistical analysis, the validation of data using concomitant systems, the design of experiments, scaling-up modeling, and electronic databases on the Internet.

This paper reports the results of the development and implementation of hands-on laboratory experiments in a newly developed laboratory for a two-semester undergraduate course in Instrumentation and Measurements in a Mechanical Engineering program. The course, designed for the undergraduate junior level, is a two-semester course for a total of four credit hours. It involves a three-hour laboratory in conjunction with a weekly, one-hour classroom lecture in mechanical engineering. A modified version of this approach, however, can easily be implemented at all levels of the mechanical engineering curriculum. The development of this laboratory began with the writing of a successful proposal for outside funding that was used to develop a hands-on teaching laboratory. Another important component of this process was the use of a two-semester long, open-ended project (OEP), where the students were required to come up with a creative approach to a problem and then design and construct a working prototype and conduct a feasibility study. Consequently, this laboratory was part of a full-cycle learning experience that began with the inception of an idea and concluded with a feasibility study of the working prototype. After the students had acquired the necessary minimum knowledge in the first semester, they began their
OEP by developing an initial idea. They then continued on through the design and construction of a working prototype (including both system and measurement sensors on prototyping boards in NI ELVIS), and concluded by conducting a feasibility study, which involved the design of the experiment, the collection and analysis of data, writing a report, and giving a presentation. Nowadays, the computer-aided NI ELVIS system is used primarily in instructional electronic and electrical engineering laboratories. Because of this, an extensive process was implemented to adapt this system to a mechanical engineering lab and satisfy the needs of a mechanical engineering program. This was accomplished by developing new experiments suited for a mechanical engineering program, newly designed and built hardware, and instructions that had been developed and built in-house using active student participation.

Laboratory Experiments

The course, designed for the undergraduate junior level, was a two-semester course for a total of four credit hours. It was conducted as a three-hour laboratory in conjunction with a one-hour weekly classroom lecture in mechanical engineering. Previously, the course used the same format, but the laboratory activities were demonstrative instead of hands-on, and the application of computer-aided measurement systems was limited. In accordance with the ABET accreditation process, the university recognized an urgent need to develop a computerized, state-of-the-art, hands-on instrumentation and measurements laboratory for these classes.

The development process of the new laboratory proceeded according to five main criteria: (1) the creation of a hands-on approach that would increase student interest and knowledge, (2) the use of computer-aided experimentation, (3) affordability, (4) the use of available resources, and (5) obtaining external financial support. The first decision involved choosing a computer-aided measurement system with sensor and transducer sets. After performing a market analysis and looking at each system’s affordability and potential as a learning tool for students, we chose to concentrate the lab activities around the use of an inexpensive, computer-aided experimentation system like NI ELVIS. This system uses prototyping boards for the building of sensors and transducers which the students were able to create from basic electronic elements according to a unique design. A statistical column had also been previously developed and designed by the author and it was built in the department’s mechanical shop (see Fig. 1). This hardware was a substantial element in the creation of the experimental station (see Fig. 2). For the laboratory class, two major activities were designed and developed: (1) a series of structured experiments, and (2) an open-ended project (OEP). Both activities were designed in such way that the students would gain hands-on experience with sensors and measurement systems. They were also designed so the students could learn about (1) data analysis with a computer-aided experimentation system for applying statistical analysis, (2) data validation using concomitant systems, (3) the design of experiments, (4) the prototyping of systems, (5) scaling-up modeling, and (6) the use of electronic databases from the Internet.

Together, the bench-top workstation and the Computer-Aided Data Acquisition System (CADAS) with the statistical column created a comprehensive and universal laboratory tool that can be used for most structured experiments, including those that involve OEP systems. Via the front control panel, the workstation provides convenient connectivity and functionality (in the form of BNC and
banana-style connectors to the NI ELVIS) with the function generator and variable power supplies. The ELVIS software routes the signals in the NI ELVIS bench-top workstation to the instruments.

Another part of the experimental system for student use, the statistical column, was designed and built in-house. This column can measure a broad variety of two-phase flow parameters (including flow-pattern related phenomena) as a random process that uses capacitive, resistive, and optical measurement systems in order to monitor flow patterns and in-situ concentration. It consists of both hydraulic and electronic systems (including ELVIS) as shown in Fig. 2. The hydraulic system consists of a vertical test tube, three measurement systems (capacitive, resistive, and optical), air pressure and flow meters, and an air compressor. The electronic system consists of a computer-aided data acquisition system (CADAS) and a prototyping board with electronic circuitry (built by students according to written instructions and using simple electronic elements) that are then interfaced to NI ELVIS. After the measurement system was built, calibrated, and interfaced successfully to ELVIS, the student groups performed the experiment by following the second part of the written instructions. There were many different experiments that allowed the students to learn various aspects of instrumentation and measurements. These experiments were also well-suited to prepare the students gradually to apply their knowledge to the development of the OEPs and to conduct the most complex class experiment (as shown in Fig. 3). In the most complex class experiment, the student, following the written instructions, built three measurement systems (capacitive, resistive, and optical), connected three sensors to the vertical test tube, and interfaced this to ELVIS (as shown in Figs. 1 and 3). After the measurement systems were built, calibrated, and interfaced successfully to ELVIS, the student group performed the experiment by following the second part of the written instructions. This part of the experiment involved gathering data for voltage signals vs. times from the three sensors for different flow patterns. The results of this are shown in Fig. 6, which shows an optical system that is controlled by air pressure and its flow rate. Using MatLab, LabVIEW, and spreadsheet software, the students calibrated the primary dynamic signals by receiving signals for concentration or film thickness vs. time and then transferring those signals into amplitude and frequency domains (Figs. 6 and 7). This was done in order to evaluate the concomitancy of the measurement systems and to answer questions about the impact of the controlled independent parameters (flowrates, pressures, etc.) on the dependent parameters (concentration, film thickness, etc.).

The decision to use capacitive, resistive, and optical sensors for the experiment was based on how frequently those three sensors are used in mechanical engineering applications for the measuring of stress, displacement, motion, pressure, temperature, concentration, film, level, surface properties, lubrication quality, cavitation, and velocity. Likewise, because this particular approach involved experiential learning and building everything from scratch, it exposed teachers and students to the key issues of instrumentation and measurements, including sensor and transducer design and application, signal conditioning, troubleshooting, calibration, computer-aided data acquisition with data analysis and validation, the design of experiments, signal analysis for deterministic and random processes, error and uncertainty analysis, and communication issues such as the analysis of electronic databases, report writing, and oral presentations.

For this hardware and software, new teaching strategies and experimental setups needed to be developed for both classes. The first four structured experiments for the first class were designed so the students would gain hands-on experience with electrical measurements and basic electronic
systems such as multimiters, signal generators, analog oscilloscopes, capacitors and resistors, Wheatstone bridges, and the computer-aided NI ELVIS system (which was used extensively in both classes). This allowed the students to understand how to use these instruments as well as how to write lab reports and proposals.

In the fifth experiment, students become familiar with using the computer-aided NI ELVIS system as a tool for obtaining and analyzing a dynamic signal measured from the statistical column. This experiment consisted of two parts. The purpose of the first part was to measure the resistance of an opto-resistor by using a board-built Wheatstone bridge. The purpose of the second part was to obtain a dynamic signal as a gas-liquid mixture was flowing through the statistical column. The signal was obtained by measuring the voltage across a Wheatstone bridge, which included an opto-resistor that was mounted perpendicular to the flow. A flashlight provided light to the opto-resistor from the opposite side of the statistical column. The voltage signal was viewed using a computer-aided digital oscilloscope, and it was recorded for low, medium, and high pressure inputs.

In the sixth experiment, students familiarized themselves with static calibration techniques and dynamic signal measurement methods. In part one, the objective was to measure the resistance of a linear potentiometer and find calibration characteristics as the displacement varied. The error was then calculated by comparing the measured resistances with the best fit line. After building a Wheatstone bridge with a thermistor, the calibration was conducted by using values that had been calculated from the manufacturer’s formula and then placing the thermistor in water with known temperatures (hot, room temperature, and cold). The voltage signal across the Wheatstone bridge that the thermistor was attached to, was then analyzed with NI-ELVIS’s digital oscilloscope. In the third part of the experiment, the thermistor was transferred from the hot water to the water at room temperature and then to the cold water. The registered transient signals were recorded and analyzed in order to find a time response to the thermistor.

In the seventh experiment, the student became familiar with measuring RPMs in a mechanical system (another typical mechanical parameter) by using a stroboscope. This experiment was also designed to allow students to use their intuition and creativity to develop an alternative measurement approach that was concomitant with the first method. The differences between the two methods was then compared and analyzed in order to validate the experimental results of the DC motor’s RPMs vs. voltage supply. Many different systems, including those based on opto-resistors or switch type sensors, were proposed and investigated. The students then conducted measurements in order to establish the compressor characteristic of flowrate vs. power supply.

The eighth structured experiment in this class was designed to familiarize students with Op-Amp circuits as well as the NI ELVIS system and its applications. This experiment was also designed to provide the knowledge that would be needed in the next semester for performing measurements of mechanical parameters as a part of a low-pass filter. Three basic operational amplifier circuits were investigated: a voltage follower, a non-inverting amplifier, and an inverting amplifier. Each circuit was tested with DC input and AC input voltages. The output voltage levels were measured and the amplitude and phase relationships between inputs and outputs were documented.

The structured experiments in the second semester class started with applying a pressure sensor application to a dynamic pressure signal from a membrane compressor using the NI ELVIS system
and prototype boards. This activity refreshed the students’ knowledge from the previous semester and allowed them to further hone their skills of dynamic signal gathering and analysis in the measurement of mechanical parameters. The students measured output voltage levels and generated calibration curves between supplied compressor voltages and pressures.

The goal of the second experiment was to prepare the students to build and use an AC bridge in the future. This required the use of a low-pass filter for interfacing into the NI ELVIS system. Students were required to build and utilize a low-pass filter for further applications including the NI ELVIS oscilloscope and prototype boards in order to measure dynamic voltage signals.

In the third experiment, students experimented with the properties and applications of low-pass filter circuits based on op-amp using NI ELVIS fixtures like oscilloscopes and prototype boards for the measurement of dynamic random signals. Students also learned how to identify the quality of gathered signals as well as how to analyze them.

In the fourth laboratory experiment, the students built an optical system on a statistical column that was interfaced to the computer, and then ran experiments of dynamic signals controlled by flow conditions in the statistical column. By building the Wheatstone bridge, the students learned how to achieve the correct sensitivity of the bridge by using a potentiometer and a photocell in order to find the correct resistance value of a Wheatstone bridge. A variety of flow patterns, including dispersed bubble flow, bubbly flow, and churn flow, were observed and analyzed. Results of this lab demonstrated how to control, observe, and analyze randomly varying voltage signals that had been impacted by the flow patterns.

The fifth laboratory experiment involved using the AC Bridge and the capacitive sensor installed in a statistical column (and interfaced via the AC Bridge to the NI ELVIS system) for the dynamic measurement of random mechanical processes. Before the main part of the experiment, students had to build and troubleshoot an AC Bridge with a low-pass filter and then use this system for the gathering of data. The first part of the lab used capacitive sensors with an AC bridge but without a low pass filter. The second part of the lab used capacitive sensors with an AC bridge with a low-pass filter. A variety of flow patterns, including dispersed bubble flow, bubbly flow, and churn flow, were observed and analyzed. Data for primary signal voltage vs. time were transferred during the calibration process to the in-situ concentration vs. time. The students also analyzed the data in time, amplitude, and frequency domains, and compared the signals with and without the filtering process.

The sixth experiment applied dynamic measurements of random mechanical process using the Wheatstone bridge and the resistive sensor (installed in a statistical column and interfaced via the Bridge to the NI ELVIS system) to gather data of in-situ concentration vs. time, which are concomitant to the data from a capacitive sensor. The concomitancy was then used to validate the measurements. The collected data was compared to the results from concomitant measurement systems as a part of the data validation process. Before the main part of the experiment, students had to build and troubleshoot a Wheatstone bridge on a prototyping board and then apply this system to the gathering of data. A variety of flow patterns, including dispersed bubble flow, bubbly flow, and churn flow, were observed and analyzed for the same flow conditions used in the fifth experiment. Data for primary signal voltage vs. time were transferred during the calibration.
process to in-situ concentration vs. time. The students also analyzed the data in time, amplitude, and frequency domains and compared the data to the data collected from the capacitive system.

Figure 1: Custom Made Statistical Columns for Experimental Apparatus (top), Partial View of the Laboratory (bottom).
Figure 2: Experimental Station. Custom Made Statistical Column for Experimental Apparatus (left), ELVIS Benchtop Workstation with Circuitry on Prototyping Board (right top), and Flow Patterns in Statistical Column (left bottom).
Figure 3: Column with a Slug Flow (top left), ELVIS Digital Oscilloscope View of a Signal from the Column (top right), and Signal Comparisons from the Column (bottom).
Figure 4: Concomitant Measurement Systems for the Final Experiments with Data Validations in an OEP.
Figure 5: Class Experiment with Data Validations. Block Diagram of the Circuitry (top), and the Bench-Top Workstation with Circuitry on the Prototyping Board (center left), and Column Experiment Set-Up (center right). Digital Oscilloscope View of the Signals from the Column (bottom).
Open-Ended Project

As part of the teaching tool in these classes, an open-ended project is used in which the issues that need to be solved are designed to be realistic, complex, state-of-the-art, and challenging. The objective is to generate and intensify enthusiasm among the students and to prepare them more substantially for the “outside” world using a discovery approach. It is crucial for the students to understand that the discovery process is one in which they are active participants, not passive observers. In processes like this, faculty members and students become learners and investigators simultaneously. Their active participation makes for a more effective learning process beneficial to both parties. At the beginning of the first semester, a full-cycle learning experience in OEPs begins with the development of an initial unique idea. It then continues on to the design and construction of a working prototype including CADAS, and concludes by conducting a feasibility study involving the design of experiments, start-up procedures, data gathering and analysis, report writing, and a presentation. This means that the OEP contains a full-cycle experiment from inception to implementation.

An effective way to begin the OEP is by selecting quality references that are feasible in a “learn approach” with limited library resources and whose full-text versions can be found on the Internet. In selecting sources, two key issues are important: (1) that the student uses objective and high quality references, and (2) that the source contains state-of-the-art information. In this case, the most important sources of information are refereed journal papers and patents. The student’s limited subject knowledge, coupled with a plethora of relatively easy accessible scientific (and mostly pseudoscientific) information on the Internet, creates a situation that requires a knowledgeable faculty member to be intensively involved during the teaching process. This includes defining the criteria for evaluating quality sources before they can be used in the learning and application processes.

Due to the broad spectrum and ready accessibility of materials on the Internet, there is also the ever-present danger of plagiarism. Consequently, the instructor should clearly explain the ethical and judicial repercussions of plagiarism. This will hopefully guide the students to police their own practices. Because OEPs require the students to do independent study on the subject and to define a unique idea using limited knowledge, another good resource is the US patent database. Because each patent must have at least one cookbook-type recipe concerning how to implement the idea, this makes patents a valuable source for students working on OEPs. However, in the case of patents the instructor needs to very carefully guide the students in their selection of good quality patents. Even though most high quality sources of information are refereed papers and technical reports, finding and evaluating these sources can often be confusing for students. After using the Compendex index, however, the potential confusion over what is and what is not a refereed paper can usually be avoided.

The OEP activities implement the following steps:

1. An introduction to the creative thinking process and its implementation by finding a solution to a challenging problem. This involves a full cycle of
activities that includes a study of the resources, brainstorming to create alternative solutions, the design and construction of the first prototype (including a feasibility study with data analysis, prototype evaluation, and redesign), the generation of an engineering report, and a final presentation which documents the design, development, testing, and evaluation of the end product\textsuperscript{1,2,3}.

2. The background search and study of closely related solutions to the issue (refereed journal papers, patents, web sources, and e-library materials), which provides comparisons to the approach and its implementation in the OEP process\textsuperscript{4,5,7,10}. Although from an educational viewpoint the quality of patents is not as good as the quality of refereed journal papers, a patent contains cook-book-type recipes concerning how to build a patented system which is very important.

3. The introduction and application of uncertainty and error analysis, which includes an error reduction process and data validation\textsuperscript{6,8,9}. Data validation is especially crucial in experimentation, not only in terms of the magnitude of errors and reduction of outliers but also consistency. The solution in this matter could be found through the use of concomitant measurements systems, which, if the results fall into the expected range, give the validation of the experimental conditions.

4. The development and calibration of necessary measurement systems\textsuperscript{8,9} based on capacitive, resistive and optical sensors with measurement systems built by students on prototyping boards from simple electronic elements.

5. The application of computer-aided experimentation and research processes using tools such as Matlab, CADAS, the Internet, Lab VIEW, spreadsheets, graphics software, and other electronic tools.

6. The prediction of results based on theory and the application of a phenomenological approach coupled with physical experimentation and experiment design in order to verify the results against the theory of assumptions used in experiments and conducted data analysis.

7. The use of computer-aided communication and the dissemination of results by writing reports, class and conference presentations, and publications.

At the beginning of the first semester, the professor issues requests for proposals and then collects them from the students. After a few attempts and changes, teams and proposals are usually accepted (teams consist of one to three students). Each team then begins to work on the OEP by performing a background literature search and analysis. Based on the search and analysis, teams design their first prototype as well as the experiments that will be used in their study program. They also define the deliverables and the success criteria for their OEP final product. During the process, there are many check points and
Fig. 6: History of the Signals, Frequency of Occurrences, Power Spectral Density (PSD) and Cumulative Power Spectral Density (CPSD) of Spatial Concentration in Dispersed, Bubbly, and Froth Flows in Statistical Columns
open labs where the student teams work on their prototypes and interact with instructors. The first significant graded checkpoint comes at the end of the MCHE 357 class (first semester). This is when each team submits their first report based on the preliminary feasibility study results and the instructor’s recommendations for changes. If the report is accepted, it is graded and returned to the students with feedback. If a report is not accepted, it is returned to the students with a list of deficiencies allowing the students to rework and resubmit the report. In the second class, the process continues. Students rebuild a preliminary prototype, conduct a feasibility study, analyze data, write a final report, and make a final presentation at the end of second semester. Figures 5 through 8 demonstrate examples of the hardware and results of analysis used in the OEPs. Very limited examples of data analysis conducted in the OEP are shown in Figures 6 and 7. Figure 8, shows the completed OEPs with final prototypes after the second semester (MCHE 358 in fall 2008). All of these prototypes were completed in the fall semester of 2008.

Fig. 7 View of an Electronic Circuitry of an AC Bridge with a Low-Pass Filter on the ELVIS Prototyping Board Build by Students for Experiments.

Figure 8: Completed OEP Systems in the Fall semester of 2008.
Summary and Conclusions

This paper has reported the results and experiences of the development and implementation of hands-on laboratory experiments in a newly-developed laboratory for Instrumentation and Measurements. The course Instrumentation and Measurements, conducted at the undergraduate junior level in the Mechanical Engineering Program, was a two-semester course for a total of four credits and took place in conjunction with a one-hour classroom lecture and a three-hour laboratory. The development process of this laboratory began with the writing of a successful proposal for outside funding for a hands-on teaching laboratory. After developing the lab’s concept, the next step involved finding the right approach and acquiring the tools that were reasonable in terms of price, size, complexity (computer-aided system), and minimal maintenance requirements. The choice was the NI ELVIS system, which is used extensively in many instructional electrical and electronics engineering laboratories. Its application within mechanical engineering programs has required the development of completely new experiments that involved newly-designed hardware, which, in this case, was developed and built in-house. The process of developing a hands-on laboratory presented difficulties in the beginning. The students were required to progress significantly in relation to their previous laboratory approaches, and all new developments had to be implemented immediately into the teaching process. Despite all of these obstacles, however, students slowly came to understand and appreciate the new learning opportunities developed in this approach.

In order to expand the students’ exposure to the practical application of knowledge and to encourage their creativity, a two-semester long, open-ended project required the students to find a problem’s solution using creative approaches. Consequently, a full-cycle learning experience took place that involved solving real, technical, state-of-the-art problems. This began with the development of an initial idea, continued through the design and construction of a working prototype (including both the system and the measurement sensors on prototyping boards in ELVIS), and concluded by conducting a feasibility study finalized by the writing of a report and an oral presentation.

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References


10. Patents can be found on the web at URL: http://www.uspto.gov/.

11. Information about the NI ELVIS can be found on the web at URL: http://www.ni.com/.