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Uncertainty Analysis and Instrument Selection Using a Web-Based Virtual Experiment

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Uncertainty Analysis and Instrument Selection using a Web-Based Virtual Experiment

Abstract

Key words: Web-based, Virtual Experiment, Instrument selection, Uncertainty Analysis.

A methodology has been developed and successfully implemented for transforming physical experiments in an undergraduate thermo-fluids laboratory at Old Dominion University (ODU), a doctoral university, into web-based virtual experiments while the Mechanical Engineering (ME) faculty at Western Kentucky University (WKU), an undergraduate university, have developed and implemented a Design of Experiments (DOE) Plan to assure that graduates of their program have acquired the skills necessary to design and conduct experiments and analyze experimental results. This paper presents details about a web-based virtual experiment designed to teach students about selection of instruments based on the uncertainty estimated from the virtual experiment.

The web-based virtual experiment, involves the measurement of frictional losses in fluid flowing in a pipe at various flow rates. In this virtual module, the student experimenter can adjust the flow rate in the pipe with a virtual flow control valve and measure both the flow rate and the pressure drop by selecting different measuring instruments. The selected instruments have corresponding measurement uncertainties and the student is tasked through various activities in the virtual experiment to evaluate which instrument is the "best fit" for the particular experimental design situation.

The web-based virtual module has been tested at ODU and an assessment of its effectiveness in student learning is provided. Student learning gains achieved through the web-based virtual module were measured by comparing the performance of a "Control" group (no access to the module) and an "Experimental" group with access to the web-based virtual module. Both groups were administered an identical multiple choice quiz and the quiz scores were analyzed to gage the effectiveness of the module in teaching students about instrument selection, and uncertainty and errors in experiments. Students in the "Experimental" group were also surveyed to get their feedback on the effectiveness of the module in aiding their learning of these skills.

Introduction

The Mechanical Engineering (ME) faculty at Old Dominion University (ODU), a doctoral university, and at Western Kentucky University (WKU), an undergraduate university, have collaborated to blend elements of web-based virtual experiments developed at ODU with an outcome based assessment plan employed at WKU. The collaboration was initiated at the workshop[1] held at ODU in the summer of 2007. At the workshop, several presenters provided detail on a methodology which had been developed and successfully implemented for transforming physical experiments in an undergraduate thermo-fluids laboratory into web-based virtual experiments[2, 3]. An attendee of the workshop from WKU, who is a member of a faculty team, which had developed and implemented a Design of Experiments (DOE) Plan[4, 5, 6] to assure that graduates of their mechanical engineering program have acquired the skills necessary to design and conduct experiments and analyze experimental results, noted the absence of several key elements of the DOE plan in the presented web-based virtual experiment modules.

Therefore, one of the outcomes of the workshop was the realization that a blending of the web-based virtual experiments and some of the elements of the outcomes based DOE Plan would be beneficial to both ME programs. It was also noted that some elements of the DOE Plan were not explicitly part of the virtual experiments, particularly the prediction of uncertainty prior to and the estimation of errors after the experimental execution. This skill and its associated consequences were not sufficiently addressed during the mapping of the physical experiments into web-based virtual experiments at ODU, and additionally, a weakness in student performance in the application of this specific skill was noted through the assessment of the learning outcomes in upper division laboratory courses at WKU. Therefore, a likely addition to the battery of virtual experiments was a module which reinforced these necessary competencies for the engineering students as they make their transition from engineering student to practitioner and the inclusion of this web-based module in the curriculum both ME programs.

Since measurement uncertainty and experimental errors are strongly dependent on the method of measuring the physical parameter and the selection of instrument to perform the measurement, these elements from the DOE Plan were also critical to student learning in these data analysis areas and therefore were also incorporated in the selected web-based virtual experiment. The physical experiment chosen focused on the measurement of frictional losses in fluid flowing in a pipe at various flow rates. In this virtual module, the student experimenter has the ability to adjust the flow rate in a section of the pipe with a virtual flow control valve while measuring both the flow rate and the frictional losses or pressure drop by selecting different instruments to measure these physical parameters. The selected instruments, which map into the specific measurement methods, also have corresponding measurement uncertainties. The student is tasked through various activities in the virtual experiment to evaluate which instrument is the "best fit" for the particular experimental design situation. Both physical and cost aspects of these selections are judged giving the student the insight into design based decisions and their associated consequences during the planning of an experiment. Another important aspect of this learning module is the distinction made between uncertainty analysis during the planning stages or the prediction of uncertainty versus the error analysis during the measurement stages in the experimental process or the estimation of error.

The web-based virtual module has been tested at ODU and an initial assessment of its effectiveness in student learning will be presented. Student learning gains achieved through the web-module were measured by comparing the performance of a "Control" group (no access to the module) and an "Experimental" group with access to the web-based virtual module. Both groups were administered an identical multiple choice quiz and the quiz scores were analyzed to gage the effectiveness of the module in teaching students about instrument selection and uncertainty and errors in experiments. Students in the "Experimental" group were also be surveyed to get their feed back about the module.

Background of the Virtual Experiments

Our vision was to develop web-based virtual engineering laboratories that will closely emulate the learning environment of physical engineering laboratories. Using recent paradigm shifts in visualization technology, together with advances in computer solutions of physical phenomena, design and implementation of truly interactive, life-like virtual experiments has become feasible. We do not suggest that a one-to-one (perfect) mapping of physical experiment into a web-based virtual experiment will ever be possible. However, by ensuring that important characteristics of the physical experiment are identified and preserved during the mapping process, a methodology will evolve that we believe to be very useful in development of web-based virtual experiment modules that can be used in physical laboratories, lecture classes and for web-based virtual laboratories for distance learning engineering programs.

For several years, students in the Thermo-Fluids Laboratory (ME 305) course have been using web-based virtual experiment modules, mimicking the physical experiment, for practice runs before performing the actual experiment. This has been shown to reinforce student learning due to module features such as interactivity as well as accessibility via the Internet, and has promoted safety due to students having more familiarity with experimental procedures. The overall quality of lab experience has improved because students are exposed to hands-on experience in both physical as well as virtual domains. Another benefit of the web-based virtual experiment module is that instructors are able to download web-based virtual experiment modules on their laptop computers in lecture classes for clarification of concepts and reinforcement of physical principles. Instead of taking students to a laboratory demonstration during a lecture, an instructor will be able to use computer-based virtual experiment modules to illuminate and reinforce basic concepts. As a result, web-based virtual experiments have demonstrated the potential of becoming powerful visualization tools in a classroom setting where an instructor can discuss "what if" scenarios as he or she performs a virtual experiment interactively. These virtual experiments have provoked classroom discussions and transform students from being passive listeners to active participants.

Finally, the proposed methodology has provided the framework for development of virtual laboratories at ODU and other institutions, and will facilitate efforts to implement web-based engineering programs. It is interesting to note that, despite technological advances, there remains a scarcity of undergraduate engineering programs available through distance learning networks. This is primarily due to difficulty in providing laboratory experience on the Internet[7]. There are only two or three distance learning engineering programs in the nation and most of them either require campus visits for laboratory courses[8] or rely on videotapes or CDROM of laboratory experiments[9] for laboratory courses. Development of real life like web-based virtual laboratories will cause distance network based undergraduate engineering programs to become more viable, and reach a diverse student population base that would not have otherwise enrolled due to geographical or other limitations.

Background on the Design of Experiments Plan

The ME faculty at WKU have developed and implemented a professional plan, which is integrated into design and laboratory courses through the freshmen to senior years. The plan has served to provide consistent and properly assessed instruction for students pursuing a baccalaureate Mechanical Engineering degree at WKU. To achieve the desired outcomes from the professional plan, it is necessary to provide students with the opportunity to acquire tools and skills, as well as technical competency[5].

The ability of ME graduates to successfully design, conduct and analyze experiments is one of the skills integrated across the ME curriculum, and is demonstrated in the execution of multiple lab experiences in senior lab courses and of the senior capstone design course. Beginning in the freshman year, students are provided with opportunities to acquire experimental, analytical and modeling tools and skills, and to develop effective means of communicating the results of their work. In an analogous fashion to the capstone design project providing a measure of the students' ability to perform a design project, the capstone experimental experience requires that students and their teams demonstrate the application of experimental abilities to set up and analyze less-defined experimental problems. To assist in the organization of course content and its assessment, the following seven components have been used to define the DOE Plan[10, 11].

1. Experimental Planning
2. Methods of Measurement
3. Selection of Instrumentation
4. Prediction of Uncertainty
5. Analysis of Data and Results
6. Estimation of Error
7. Reporting of Experimental Results

These components are described more completely in the assessment rubric, shown in Table 1. Student work from experimentation classes in the sophomore, junior and senior years are then assessed to determine the ability of the students to successfully apply each component. The courses that provide students with instruction in these components, or the opportunity to demonstrate proficiency are offered throughout all four years of the curriculum. In early-level courses, students are first introduced to experimental tools, techniques and practices. Emphasis is placed on gaining experience with equipment, following stated procedures, and processing and presenting results effectively.

Upper-level students are expected to synthesize and incorporate experiences into determining proper lab procedures and techniques. Greater emphasis is placed on analyzing the data and results, and performing uncertainty and error analyses. By the time students take the capstone design course, they are expected to be able to completely specify, plan, conduct, and analyze experimental situations. Senior student teams are expected to completely perform all of the components of design of experiments, from the definition of a problem, to the set-up and execution of procedures, and the communication of properly analyzed results.

The assessment rubric shown in Table 1 is used for evaluation of student work, and laboratory and design courses are selected to capture the evolution of student progress from sophomore through senior years. Assessment of the above learning components for the past five years have shown continuous improvement and sustained competency in components 1, 2 and 7 but less so for components 3, 4, 5 and 6. Students can execute the methodology of first and second level uncertainty and error analysis[11, 12] but have demonstrated inappropriate application of analysis of the experimental data, which either suggests some conceptual disconnect or limited opportunities for application in the area of data analysis. Additional opportunities for students to practice these methods, but more importantly to link the selection of an instrument to the prediction of experimental uncertainty prior to and subsequently to the estimation of the errors during the execution of an experiment, were needed to reinforce these learning outcomes. The web-based module described in the next section was designed to provide students with these practice opportunities.

Overall Layout of the Web-Based Virtual Module

The main screen of the virtual module is shown in Fig. 1. This screen is the entry point for the student experimenter.

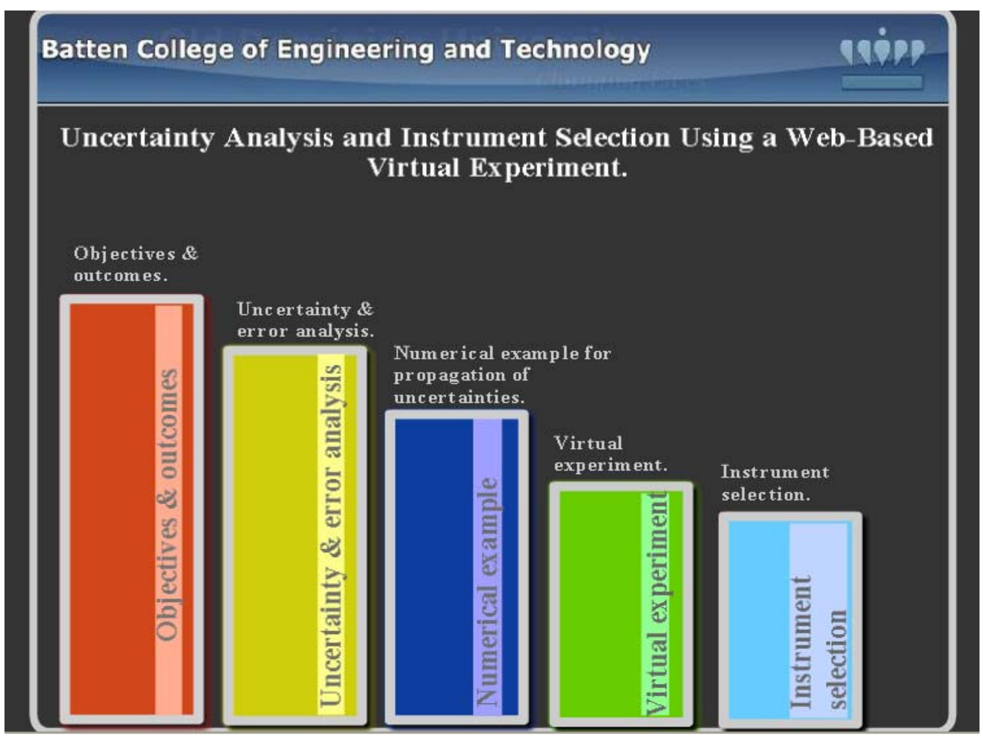


Figure 1: Main Screen of the Virtual Module

As shown in Fig. 1, the virtual module consists of five main sections each of which have their own unique structure. The main sections include:

- Objectives and outcomes
- Uncertainty and error analysis
- Numerical example for propagation of uncertainties
- Virtual experiment
- Instrument selection

The sections are designed in a way such that there is no loss in the continuity in the subject matter when one moves from one section to the other section of the module. Navigation through the module is fairly simple. One can enter any of the main sections by clicking on the rectangular bar on the main screen. Upon entering one of the main sections, navigational tools like links, arrow keys are provided that can be used to move within a main section or directly from one main section to another. The five main sections listed above are explained in detail in these following sections. The web-based module can be accessed at the following web address (http://www.mem.odu.edu/instrumentselection/dashboard-new3.swf).

Objectives and Outcomes

The objective and outcomes section is shown in Fig. 2. The basic objective of the module is to make the student aware of the fact that any measurement will always have an associated uncertainty to it and that this uncertainty can be to the most part, quantified and then used in instrument selection. The point that errors are the primary source of all uncertainty is also emphasized.

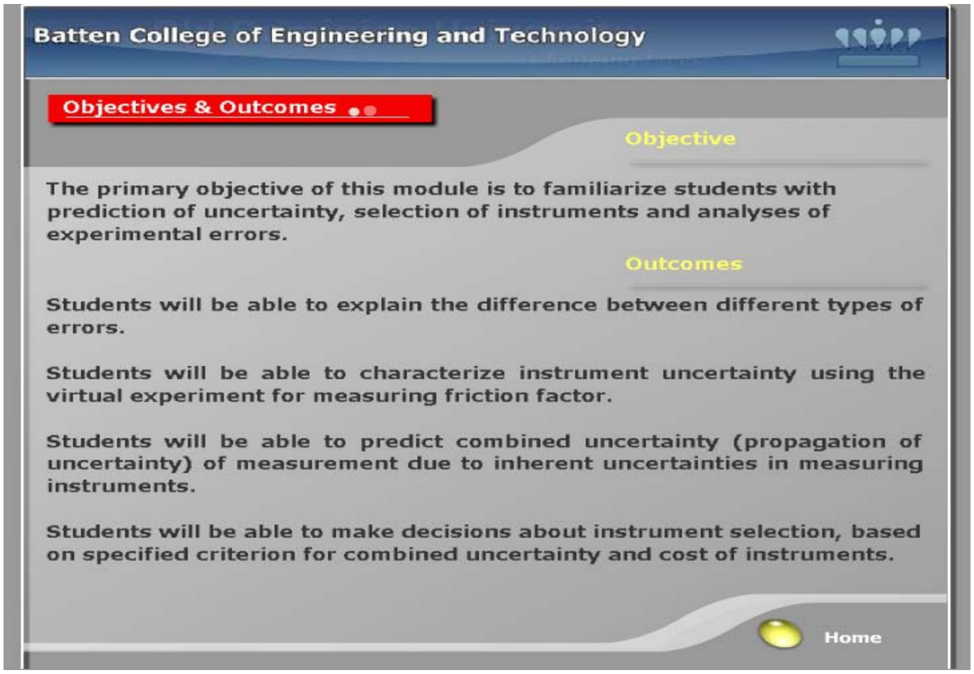


Figure 2: Objectives and Outcomes

After having gone through the entire virtual module the student will have the ability to predict combined uncertainties in experimental results by making use of mathematical tools and statistical procedures. He/she will also have the knowledge or the skill to use these uncertainty values in instrument selection where the cost of the measuring device becomes an important factor. All of these together form the expected outcomes from the virtual module.

Uncertainty Analysis and Numerical Example

The main section "Uncertainty and error analysis" provides the student with information about the characteristics of measurements, types of errors, sources of error etc. A graphical representation of the errors [11, 12] in an experiment is also included. The mathematical formulation[11, 12] for calculating overall uncertainty for a function (R) having n variables, using both the first order method and root of the sum of the squares (RSS), has also been provided in this section.

A numerical example involving combined uncertainties has been provided in the main section "Numerical example for propagation of uncertainties". Prior to the virtual pages on the numerical example, a detailed derivation for overall uncertainty in friction factor with two measured variables has been provided. The numerical example has been included in the virtual module with the intention of making the student realize the applicability and usage of the uncertainty analysis in practical situations. The problem posed as the numerical example can be read from Fig. 3.

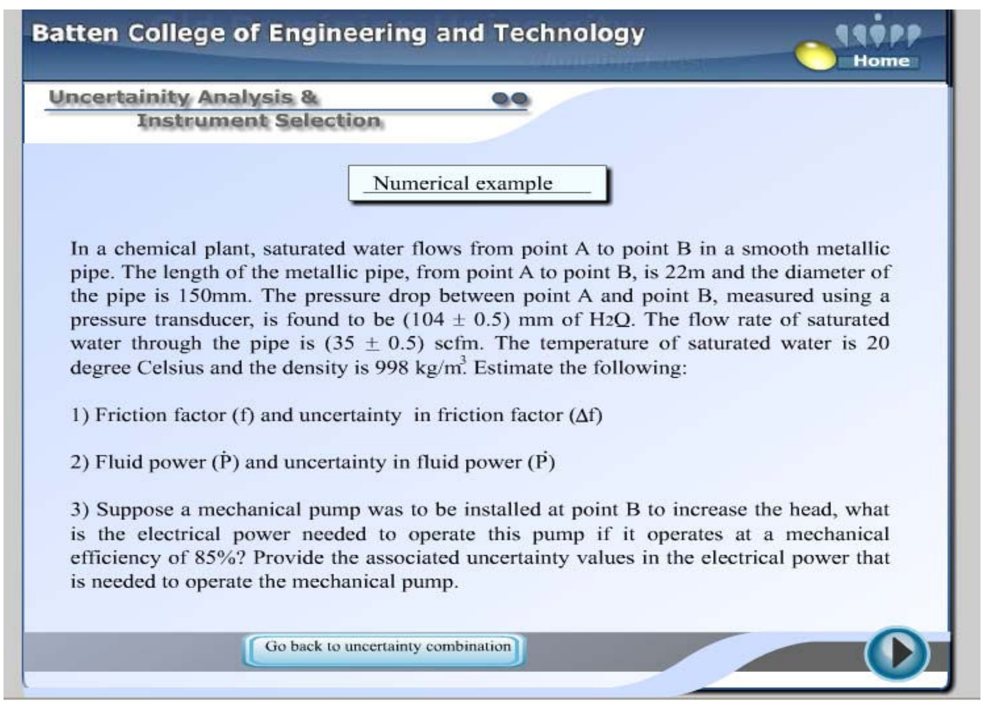


Figure 3: Numerical Example in the Virtual Module

Description of the Virtual Experiment

The section on virtual experiment can be entered by clicking on the bar under "Virtual experiment". This section is structured in a way where the student is first exposed to the equations used in determining friction factor in a pipe. The equation used in estimating uncertainty in friction factor is also listed and a link is provided below the equation so that the student can access the derivation of the equation. The nomenclature of the terms in a given equation is provided whenever required. As mentioned earlier, the virtual pages in this section and elsewhere are laced with links, arrow keys etc., in order for one to navigate within a section or from one section to another without traversing through the main screen. These navigational tools help in maintaining the continuity of information flow to the reader. Finally, a step-by-step procedure on how to conduct the virtual experiment along with details about the apparatus has been provided. All of the above information is placed prior to the page containing the virtual experiment so that one gets to peruse through this material before conducting the virtual experiment. By clicking on the link, "Go to Virtual Experiment", the student enters the virtual page that shows an array of combinations of flow meters and pressure measuring devices (Fig. 4) all of which can be used to perform the same experiment – "Friction factor in pipes".

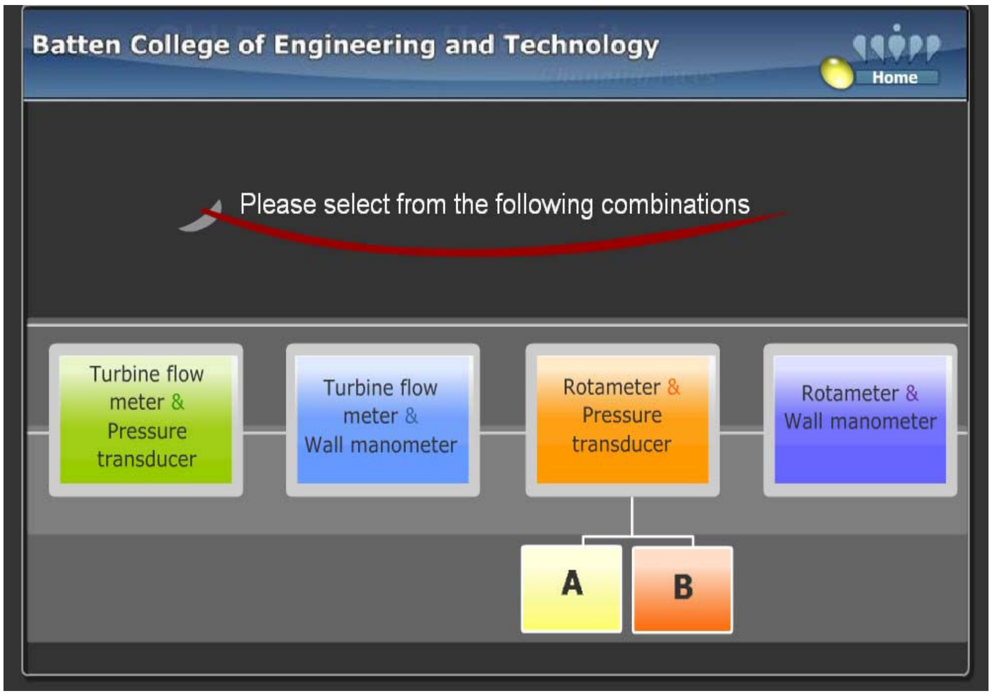


Figure 4: Screen showing the combinations of flow meters and pressure sensing devices.

The equation for friction factor (f) is given below[13]:

$$f = \frac{\pi^2 (PD) D^5}{8 \rho L \dot{Q}^2} \tag{1}$$

In the above equation, the values for volumetric flow rate $(\dot{Q})$ and the pressure drop (PD) are obtained by performing the virtual experiment. The rest of the terms in the expression for (f) are constants whose values can be obtained from the step-by-step procedure provided earlier. As a result, the same experiment can be performed for different combinations of flow meters and pressure measuring devices. This illustrates the point that the value of the overall uncertainty in any experiment depends on the accuracy of the individual measuring instruments that are used to record data while conducting the experiment. The student is able to select any combination by clicking on the box that bears the name of that particular combination (Fig. 4). By clicking on one of the boxes, the student enters the virtual experiment page as shown in Fig. 5.

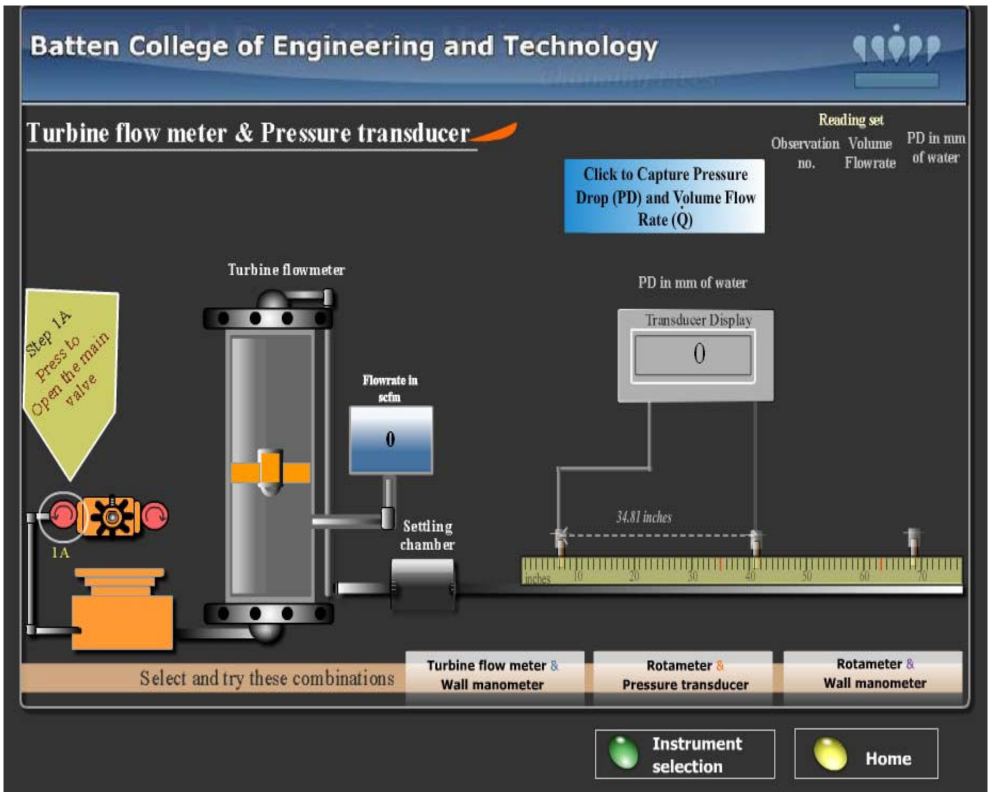


Figure 5: Set Up of the Virtual Experiment "Friction factor in pipes"

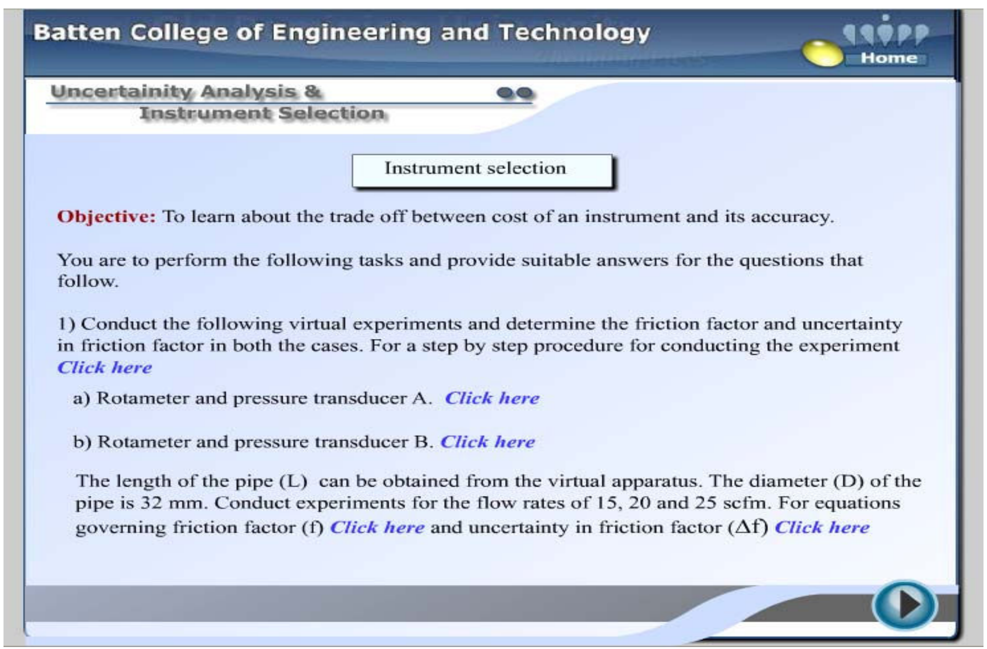
The virtual apparatus is based on the actual apparatus used to conduct the friction factor experiment. Using this virtual apparatus, the student can obtain the raw data from which he/she is able to calculate friction factor (f) and the associated uncertainty (Δf). With regards to the operation of the virtual apparatus, the student can refer to the procedure where details to do the same has been provided. The method to perform the experiment is more of less the same for all the combinations that are shown in Fig. 4.

Instrument Selection based on Uncertainty Analysis

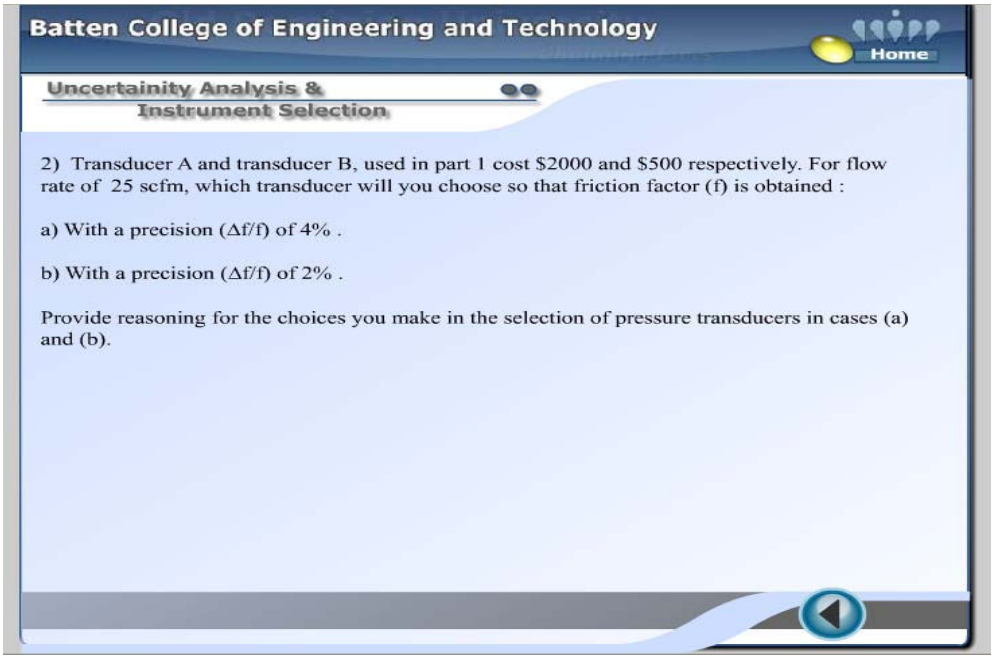
The "instrument selection" section is the last main section of the virtual module. This section plays a key role in achieving the intended objective and outcomes of the entire virtual module.

In this section, the student is asked to perform two inter-related tasks. In the first task the student is required to perform the virtual experiment for certain specific combinations of flow meters and pressure measuring devices and then calculate friction factor (f) and uncertainty in friction factor (Δf). These specific combinations include two pressure sensing devices (transducer A and B) and the rotameter which is used as a common flow meter for both the transducers. The virtual experimental set-up for these combinations can be accessed either by clicking on "Click here" (Fig. 6a) or by using the virtual page as shown in Fig. 4.

In the second task, assigned to the students as a web-based project, the cost of both transducers A and B is provided (Fig. 6b). Then the student is posed with two scenarios where the level of accuracy that is required in the friction factor (f) varies and the student is asked to choose a transducer for both scenarios and also provide suitable reasons for the choices made. In order to successfully perform this task the student has to take into account the uncertainty in friction factor and the cost of the transducer. With the completion of these two tasks in the "Instrument selection" section, the student is able to learn about the trade off that exists between the cost of the instrument and its accuracy.



(a)



(b)

Figure 6: Tasks involving Instrument Selection

Assessment of the Web-Based Module

The web-based virtual module dealing with topics related to experimental uncertainty analysis and instrument selection was implemented during the fall 2009 semester in the undergraduate thermo-fluids laboratory course in the mechanical engineering curriculum (ME 305) at ODU. The module was used in the supplementation mode wherein a group of students designated as the "experimental" group used it in addition to the conventional approach of introducing this topic through a lecture class and a lab book. The other group of students not using the module was designated as the "control" group and they learnt the topical area through a lecture and a lab book. Three sections of the laboratory course were offered, and one entire section of the course was designated as the "Experimental" group (n=15) and the remaining two sections were designated as the "Control" Group-I (n=14) and the "Control" Group-II (n=13).

This categorization was done in a random manner at the beginning of the semester, without access to students' demographic data at that time. The one lecture session embedded in the course discussed various concepts related to errors, uncertainty analysis and propagation of uncertainty. The web-based module, through examples, virtual experimentation and a web-based mini-project was used to reinforce these concepts for students belonging to the "Experimental" group. At the end of the semester, the two "Control" groups and the "Experimental" group were administered an identical two hour long multiple choice test in which 60 percent of the questions were directly related to the module topical areas. Figure 7 shows the average scores for both "control" and "experimental" groups.

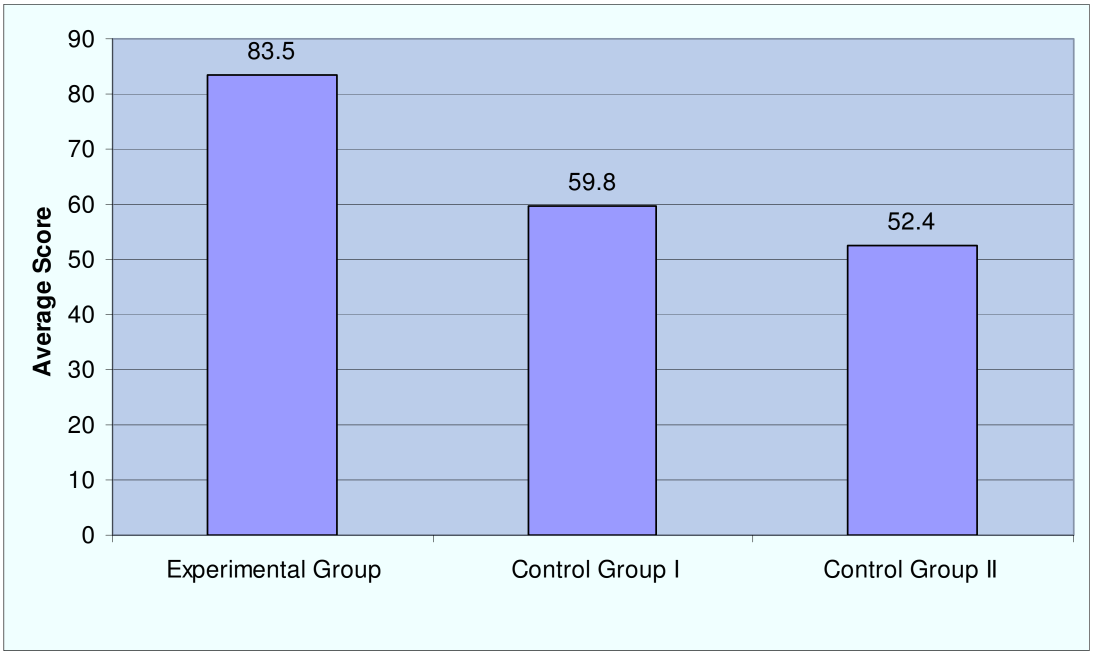


Figure 7: Average Scores for Experimental and Control Groups

From the figure it is noted that the average test score of the "Experimental" group is higher by 40% and 59% respectively when compared to the "Control" Group-I and the "Control" Group-II respectively. This indicated higher level of learning for students belonging to the "Experimental" group.

Students belonging to the "Experimental" group were also surveyed to solicit their opinions about various aspects of the module. A survey form consisting of 10 questions listed in Table 2 was developed and administered after completion of the web-based mini-project assigned to students before the final test. The student responses were assigned numerical values on the Likert scale of 5 to 1 with 5 corresponding to "strongly agree," 4 to "agree," 3 to "neutral," 2 to "disagree" and 1 to "strongly disagree."

The averages of all responses for each question are given in the last column of Table 2 along with the frequency distribution. The average of all questions was 3.95, indicating that students are generally in agreement that the web-based module is an effective tool in enhancement of learning of concepts related to uncertainty analysis and instrument selection.

Conclusion

The Mechanical Engineering faculty at ODU and WKU have collaborated to blend elements of web based virtual experiments developed at ODU with an outcome based assessment plan, which assesses components of a Design of Experiments plan, implemented at the WKU. A web-based virtual module on uncertainty and error analysis and instrument selection was developed for and implemented in a thermo-fluids laboratory course at the ODU. Student learning was compared through the performance on a two hour long multiple choice test in which 60 percent of the questions were directly related to the module topical areas for two "Control" groups with no access to the module and an "Experimental" group with access to the web-based virtual module.

From these comparisons, one can draw the inference that the improvement in student learning gain as measured by the test results for the student group with module access is significant. Additionally, students in the "Experimental" group were also surveyed to get their feed back about the module. The average of all questions was 3.95, indicating that students are generally in agreement that the web-based module is an effective tool in enhancement of learning of concepts related to uncertainty analysis and instrument selection.

The next phase of this investigation will be the implementation of the web-based virtual module on uncertainty and error analysis and instrument selection in a fall 2010 semester lab course at WKU. The results of this implementation will be similarly analyzed and reported at a future American Society for Engineering Education (ASEE) conference.

Acknowledgement

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Attributes	Absent (0)	Novice (1): Use material or instructions provided	Intermediate (2): Implement from moderately complete instructions	Proficient (3): Implement on own with minimal instruction.
Experimental Planning: Be able to define problem, evaluate measurement needs, and organize execution of project.				
Method of Measurement: Be able to investigate, justify and select measurement approach.				
Selection of Instrumentation: Be able to specify, acquire and use measurement tools.				
Analysis of Data and Results: Be able to organize, synthesize, and present data. Infer meaningful conclusions from results.				
Uncertainty and Error Analysis: Be able to assess the proper level of confidence in results and recommend modifications to change uncertainty or reduce errors.				
Reporting of Experimental Results: Be able to professionally document results, evaluate audience, and accurately convey process and product of experiment.				
Total Score: (Expect 6 for Sophomores, 12 for Juniors and 15 for Seniors)				

Table 1: Assessment Rubric for Design of Experiments

No.	Questions	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	Average Response
1	The Visualization model was helpful in understanding fundamental concepts related to friction factor	1	13	0	1	0	**3.93**
2	The Visualization model has improved my problem solving skills with respect to uncertainty analysis	3	8	3	1	0	**3.86**
3	The Visualization model exposed me to information not readily available in textbooks or lectures.	2	7	5	1	0	**3.66**
4	The model helped me understand the tradeoff between instrument cost and precision	2	10	3	0	0	**3.93**
5	The Visual images in the model will help me retain concepts and other related information for a longer period of time	4	7	3	1	0	**3.93**
6	The Visualization model provided a real life context through the numerical example that made concepts easier to comprehend	3	9	2	1	0	**3.93**
7	The time allocated for studying the visualization model was adequate	7	7	1	0	0	**4.40**
8	It is recommended to use the visualization model in future classes	5	6	2	2	0	**3.93**
9	The Visualization model was user friendly	6	4	3	2	0	**3.93**
10	More visualization modules of the type presented here should be developed for other topical areas	4	8	3	0	0	**4.06**

Table 2: Likert Survey Results of Student Learning with Web-Based Module