

UNCERTAINTY ANALYSIS AND INSTRUMENT SELECTION USING A WEB-BASED VIRTUAL EXPERIMENT

Praveen D. Malali¹, Pooja Bais¹, Robert E. Choate, III², Sushil K. Chaturvedi¹, Jaewan Yoon³

¹Department of Mechanical and Aerospace Engineering, Old Dominion University.

²Department of Engineering, Western Kentucky University.

³Department of Civil and Environmental Engineering, Old Dominion University.

Abstract

This paper presents details of 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 measurement of frictional losses in a fluid flowing in a pipe at various flow rates. Using the virtual module, a 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 their inherent 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 implemented and assessed for student learning effectiveness related to measurement uncertainties and instrument selection. Student learning gains achieved through the web-based virtual module were measured by comparing the performance of two “Control” groups (no access to the module) and an “Experimental” group with access to the web-based virtual module. All three groups were administered an identical multiple choice quiz and the quiz scores were analyzed to gauge the effectiveness of the module in teaching students about instrument selection, and uncertainties and errors in experiments. Analysis of assessed data indicates that student learning gains due to incorporation of the virtual module are statistically significant.

Introduction

Web-based virtual laboratories (WBVLs) are increasingly finding applications in the fields of engineering education [1-5], science education [6-7] and medical education [8]. In engineering education, the focus of the present study, virtual labs have been used for illustration of physical phenomenon in lecture classes as well as for supplementation of engineering laboratory courses. Many previous studies have reported results in which physical experiments have been mapped into two-dimensional as well as three-dimensional virtual reality environments [1, 2, 9, 10]. Endowed with interactivity, and accessibility via the Internet, virtual labs have enabled users to conduct experiments entirely in the virtual domain. There has also been development in recent years in the area of remotely controlled physical labs in which a distance learner, using the Internet, can conduct a physical experiment in a laboratory at a remote location [11-12]. Even though this alternative may be more desirable due to involvement of physical hardware, it has limited application in engineering education due to extensive and cost prohibitive modification of physical apparatus to make it Internet ready.

In contrast, WBVLs are more cost effective since they do not involve physical hardware except those needed for Internet connectivity and display of virtual experiments on a computer screen. The authors concede that virtual labs, no matter how advanced they may be, cannot replicate the physical laboratory environment due to WBVLs’ inability to adequately incorporate tactile, olfactory, visual and auditory features of a physical experiment. Since most engineering faculty subscribe to the

prevalent thinking that hands-on experience for students, an important feature of any engineering degree program, can best be provided by physical laboratories, using virtual labs in lieu of physical labs is not a feasible option. More research and development leading to creation of life-like virtual labs closely mimicking physical labs is needed before incorporation of stand-alone virtual labs in engineering curricula becomes a reality. Consequently, recent work related to virtual labs has been in niche areas where their accessibility, interactivity and low-cost features can be used to supplement student learning in physical laboratory courses. In this modality, both physical and virtual labs are used in tandem so that synergy created by this combination would enhance student learning effectiveness in engineering laboratory courses. This has been referred to as the use of virtual labs in the supplementation mode. One application involves creating web-based virtual labs that can be used by students for practice sessions prior to physical laboratory sessions [1-2].

The present paper describes a web-based virtual experiment that has been designed to teach students about experimental measurement uncertainties and instrument selection. In order to illustrate concepts related to measurement uncertainties, the classical experiment dealing with frictional losses in pipe flows has been virtualized and incorporated in the web-based experimental uncertainty module presented and discussed in this paper. In this virtual module, a student experimenter has the ability to adjust the flow rate in a section of the pipe with a flow control valve while measuring the flow rate and the pressure drop due to frictional losses. These physical parameters can be measured by selecting different instruments available in the module. The selected instruments have their own inherent 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. Instrument precision and cost aspects are factored in, giving students insight into

design based decisions and associated consequences during the planning of an experiment. Another important aspect of this learning module is the distinction made between uncertainty versus the error analysis during the measurement stages in the experimental process.

The web-based virtual module has been implemented and assessed for its effectiveness in enhancing student learning. Student learning gains achieved through the web-module were measured by comparing the performance of two “Control” groups (no access to the module) and an “Experimental” group with access to the web-based virtual module. These groups were administered an identical multiple choice quiz and the quiz scores were analyzed to gauge the effectiveness of the module in teaching students about instrument selection and uncertainty and errors in experiments. The following sections describe the virtual module and the assessment of the results pertaining to it.

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 navigation through the module.

As shown in Fig. 1, the virtual module consists of five main sections. Each section has a 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 of 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

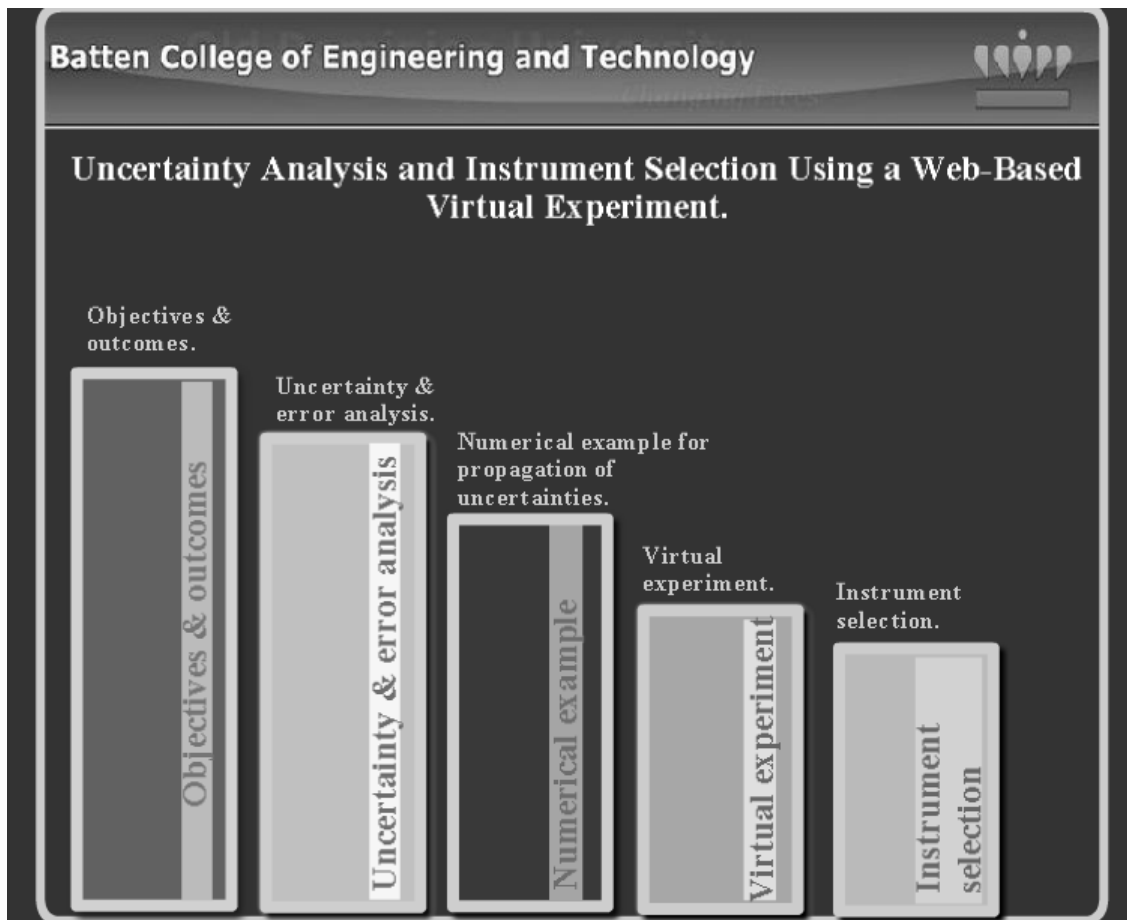


Figure 1: Main Screen of the Virtual Module.

tools such as links and arrow keys are provided to facilitate navigation 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.edu/instrumentselection/dashboard-new3.swf>).

Objectives and Outcomes

The basic objective of the module is to make students aware of the fact that measurements always have associated uncertainties and these uncertainties can be quantified and eventually used in the instrument selection process.

After having gone through the entire virtual module the students are expected to have the ability to predict the 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 as an input to the instrument selection process in which the cost of the measuring device also becomes an important factor.

Uncertainty Analysis

The 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 [13] in an experiment is also included. The mathematical formulation for calculating overall uncertainty [14] for a function (R) having ‘n’ variables, using both the first order method and root of the sum of the squares (RMS) [15], has been provided in this

section. A numerical example involving combined uncertainties has also been included. Prior to the virtual pages on the numerical example, a detailed derivation for overall uncertainty in friction factor due to two measured variables has been provided.

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 such a way that the student is first exposed to the equations used in determining friction factor in pipe flows. The equation used in estimating uncertainty in friction factor is also listed and a link is provided below the equation so that the students can access the derivation of the equation. A step-by-step procedure on how to conduct the virtual experiment along with details about the apparatus has been provided. All 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”, one can enter the virtual page that shows an array of combinations of flow meters and pressure measuring devices (Fig. 2) all of which can be used to perform the same experiment – “Friction factor in pipes”.

The equation for friction factor (f) is given below [16]:

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

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

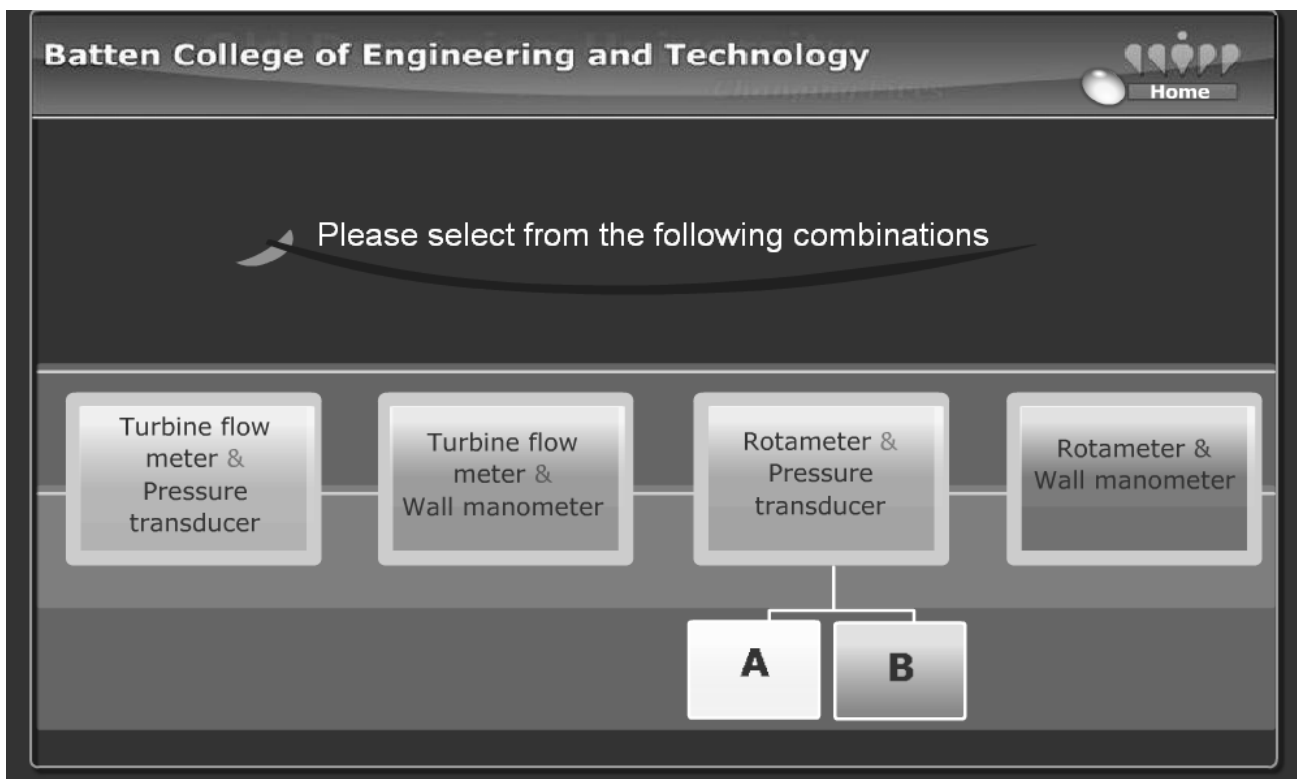


Figure 2: Screen showing the combinations of flow meters and pressure sensing devices.

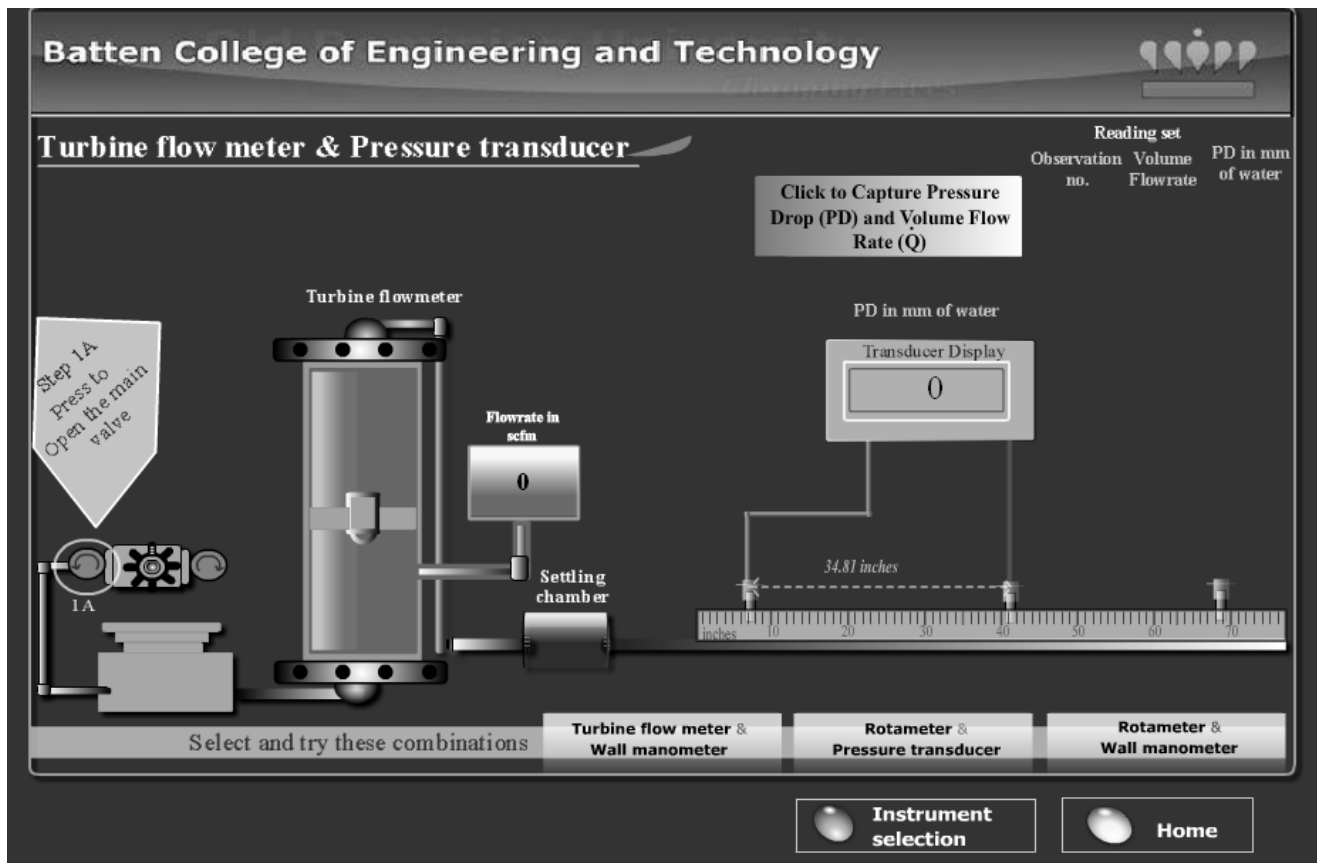


Figure 3: Set Up of the Virtual Experiment “Friction factor in pipes”.

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 to illustrate the point that the value of the overall uncertainty in any experiment depends on the accuracy of the individual measuring instruments. Students are able to select any of the four combinations by clicking on the box that bears the name of that particular combination (Fig. 2). By clicking on one of the boxes, the student enters the virtual experiment page as shown in Fig. 3.

The virtual apparatus is designed to mimic the actual apparatus used to conduct the friction factor experiment in the thermo-fluids laboratory. 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).

Instrument Selection based on Uncertainty Analysis

The “instrument selection” section is the last main section of the 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 to calculate friction factor (f) and uncertainty in friction factor (Δf). Two specific combinations used in the instrument selection project include two pressure sensing devices (transducers A and B) and the rotameter which is used as a common flow meter for both the transducers. The virtual experiment set-up for these combinations can be accessed through the virtual page shown in Fig. 2. In the second task, assigned to the students as a web-based project, the cost of both transducers A and B is provided. Students are then posed

with two scenarios in which the levels of accuracy that is required in the friction factor (f) are different and the student is asked to choose a transducer subject to cost constraints provided in the project. In order to successfully perform this task students have to take into account the uncertainty in friction factor as well as the cost of the transducer. With the completion of these two tasks in the “Instrument selection” section, students are able to learn about the trade off that exists between the cost of the instrument and its accuracy.

Assessment of the Web-Based Virtual Module

The web-based virtual module dealing with experimental uncertainty analysis was implemented during the fall 2009 semester as a part of the undergraduate thermo-fluids laboratory course in the mechanical engineering curriculum at ODU. Three sections of the laboratory course were offered, and one of the sections was designated as the “experimental” group ($n = 15$). The remaining two sections were designated as the “control” group-I ($n = 14$) and the “control” group-II ($n = 13$) respectively. The virtual experiment module was used in the “supplementation” mode where students in the “experimental” group used it in addition to the conventional approach of learning about the experimental uncertainty topic from a lab manual and a 90 minutes lecture. Students in the two “control” groups did not have access to the web-based module and they learned the topical area through a 90 minute lecture and the lab book.

For all three groups, students knowledge of the subject area was assessed through a multiple choice test that consisted of problems related to uncertainty analysis and, instrument selection. The average test scores for the “control” group-I, the “control” group-II and the “experimental” group were 59.8%, 52.4% and 83.5% respectively. Students in the “experimental” group performed comparatively better on the test as compared to students in the two “control”

groups. However, to rule out chance as a factor for explanation of enhanced learning effectiveness of the “experimental” group, further analysis of test results, using statistical methods, was performed. The primary objective of the statistical analysis was to establish beyond reasonable doubt that same results (namely improvement in student learning effectiveness) can be consistently reproduced due to the use of the virtual module. This was addressed by performing the test of hypothesis and calculation of p-values from the statistical analysis of test results. Prior to performing the test of hypothesis, the data sets were subjected to a normality check using the Shapiro-Wilk W statistics [17] at a confidence level of 0.05. The check revealed the existence of normal and non-normal tendencies in the data sets. This rendered the standard parametric and general linear models inapplicable. Therefore, a non-parametric method, the Wilcoxon’s Rank sum [17] at a confidence level of 0.05 was used for the test of hypothesis. For each student group pair (Table 1), the null and the alternative hypothesis were $H_0: \mu_1 = \mu_2$ and $H_a: \mu_1 \neq \mu_2$ respectively. The statistical parameters μ_1 and μ_2 represent the mean test scores of the individual student groups compared in the test of hypothesis in the order of their occurrence. Based on the results obtained from the Wilcoxon’s Rank sum rule at a confidence level of 0.05, the null hypothesis for all the three student group pairs was rejected. Table 1 summarizes the final results.

Table 1: Results from the test of hypothesis.

No.	Student group pairs	p-values
1	Control group – I vs. Control group - II	0.225
2	Experimental group vs. Control group - I	0.001
3	Experimental group vs. Control group - II	0.0052

Though the null hypothesis for the student group pair, Control group-I vs. Control group-II, was rejected, the p-value for the same suggests a

considerable risk in such a rejection. However, the risk in rejecting the null hypothesis is low for the other two student group pairs. This shows that the student learning in a general system can be enhanced with reasonable success using the virtual module.

Based on the discussion thus far one can attribute the enhanced learning effectiveness of the “experimental” group to the usage of the virtual module. However, it is possible that certain demographic factors other than the virtual module may have also influenced learning effectiveness of students in the “experimental” group. The demographic factors considered in this study are: gender, ethnicity, student entry status (freshman or transfer), age, cumulative GPA, “SAT-II” score and the high school GPA. Statistical significance of these factors on student learning effectiveness was analyzed using the non-parametric Wilcoxon rank sum statistical method. The results showed that of the seven demographic factors only two, namely the high school GPA and the cumulative GPA were statistically significant. In other words, in addition to the virtual module, they also contributed to enhanced learning effectiveness. For instance, students with higher cumulative GPA performed better when using the module. On the other hand, gender, ethnicity, age, SAT-I score and student entry status turned out to be not significant. These factors, according to statistical analysis, do not contribute to enhanced student learning.

Students belonging to the “Experimental” group were 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

A web-based virtual module dealing with the topics of uncertainty analysis and instrument selection was developed and implemented in the thermo-fluids laboratory course at ODU. In order to determine the impact of the virtual module on student learning effectiveness, student performance was compared on a multiple choice test in which questions were related to the module topical areas. Comparison of test results for the three groups, the two “control” groups and the “experimental” group, indicates that not only the average test score for the “experimental” group is higher than the average test scores for the two “control” groups, but also the increase in the average score is statistically significant, as indicated by a p value less than 0.05. In other words improved performance for the “experimental” group is solely due to the introduction of the virtual module and not due to the chance factor. A demographic factor analysis was also performed to see if certain factors analyzed in this study have any impact on improved student learning effectiveness. Of the seven demographic factors considered in this study (gender, ethnicity, age, HS GPA, cumulative GPA, SAT-I score and student status at entrance to the university) only the HS GPA and the cumulative GPA have an effect on enhancing student learning effectiveness that is statistically significant. To put it differently, the module is neutral to the remaining five factors, and in the case of gender it works equally well for both male and female students. The results showing that high cumulative GPA and high HS GPA students perform better with the module compared to the low cumulative GPA and the low HS GPA

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 module 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.

students is not surprising since higher GPA students tend to spend more time studying and this makes it more likely that the web-based virtual module received higher level of attention from students with higher academic performance level. Additionally, students in the “Experimental” group were also surveyed to get their feedback 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.

Acknowledgements

This work was supported by the NSF grant EEC-530365. Any opinions, findings, conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Bibliography

1. Chaturvedi, S.K et al., "Mapping of a Thermo-fluids Laboratory Experiment into a Web-based Virtual Experiment for Application as Pre-lab Practice Tool", *Innovations 2007: World Innovations in Engineering Education and Research*, Chap. 28, Aug. 2007.
2. Chaturvedi, S.K and K. Dharwadkar, "Simulation and Visualization Enhanced Engineering Education Development and Implementation of Virtual Experiment in a Laboratory Course", *ASEE Conference*, 2010.
3. Bhargava et al., *Web-Based Virtual Torsion Laboratory*, Wiley Periodical Inc. 2006.
4. Jia, R., et al., "A Virtual Laboratory on Fluid Mechanics", *ASEE Annual Conference*, 2006.
5. Buddu, M., "Virtual Laboratories for Engineering Education", *International Conference on Engineering Education*, Aug. 2002.
6. Wu, Y. et al., "Web-Based Virtual Reality Physics Laboratory", *Proceedings of the 3rd IEEE International Conference on Advanced Learning Technologies*, 2003.
7. Shin, Y., *Virtual Reality Simulation in Web-Based Science Education*, Wiley Periodicals 2002.
8. Scerbo, M.W. et al., "A Virtual Operating Room for Context Relevant Training", *Proceedings of Human Factors and Ergonomics Society, Annual Meeting*, 2007.
9. Messner, J.I. et al., "Using Virtual Reality to Improve Construction Engineering Education", *Proceedings of ASEE Annual Conference*, 2006.
10. Bell, J.T. and Fogler, H.S., "Virtual Reality in Chemical Engineering Education", *Proceeding of the 1998 ASEE North Central Section Meeting*, Detroit, Michigan.
11. Azad, A.K.M., et al., "Internet Based Experiments for Physical Laboratory Set-Up," *Proceedings of the 2003 American Society of Engineering Education Annual Conference and Exposition*, Session No. 2003-2158.
12. Rohrig, C., and Jochheim, A., "The Virtual Lab for Controlling Real Experiments Via Internet," *Proceedings of the 11th IEEE International Symposium on Computer-Aided Control System Design*, 1999, Hawaii, USA, pp. 279-284.
13. Holman, J.P., 2001, *Experimental Methods for Engineers*, McGraw-Hill, Boston.
14. Wheeler, A.J. and Ganji, A.R., 1996, *Introduction to Engineering Experimentation*, Prentice Hall, Englewood Cliffs, NJ.
15. Coleman, H.W. and Steele, W.G., *Experimentation, Validation, and Uncertainty Analysis for Engineers*, John Wiley & Sons, Inc., Hoboken, NJ.
16. Frank M. White, 1999, *Fluid Mechanics*, McGraw Hill, Boston.
17. Montgomery, C. D. and Runger, C.G., 2010, *Applied Statistics and Probability for Engineers*, John Wiley & Sons, Inc., Hoboken, NJ.

Biographical Information

Praveen D. Malali is a PhD candidate in the department of mechanical and aerospace Engineering. His research interests are in the areas of fluid mechanics, renewable energy resources and engineering education. He has also taught the undergraduate thermo-fluids laboratory at Old Dominion University.

Pooja Bais was a research assistant in the mechanical engineering department on an engineering education project funded by the division of Engineering Education at NSF. She has completed her masters' degrees in information technology and business administration from Old Dominion University.

Robert E. Choate, III is an Associate Professor of Mechanical Engineering at Western Kentucky University. He teaches thermo-fluid and professional component courses, including Thermodynamics, Fluid Mechanics and its lab, and the ME Senior Project Design course sequence. Prior to his appointment at WKU, he had a twenty year engineering practice at IBM, Ericsson Telecom and CMAC designing thermal management solutions for telecommunication, data communication and information technology equipment.

Sushil K. Chaturvedi is a professor in the department of mechanical and aerospace engineering, Old Dominion University. His teaching and research interests are in the areas of thermodynamics, solar energy, energy conversion and engineering education. He has also directed several NSF projects in the area of engineering education and virtual laboratories.

Jaewan Yoon is an Associate Professor of Civil and Environmental Engineering at Old Dominion University, and his research areas include stochastic theory in water resources, water quality model and management, meso- and macro-scale physical parameter modeling and simulation, massive spatiotemporal simulation and statistical modeling. His previous research has been funded by various federal and state agencies including USEPA, USDoD, USDoE, USDI, USDA, USGS, USACE, ONR, VDOT and NSF.