2006-628: A REVIEW OF THE CURRENT STATUS AND CHALLENGES OF VIRTUAL EXPERIMENTATION

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A Review of the Current Status and Challenges of Virtual Experimentation

Abstract
Virtual experimentation generates reactions of great enthusiasm and trepidation among engineering educators. Many educators see wide ranging applications of these techniques with advantages in terms of learning pedagogies, equipment costs, and online education. However, there are several well-founded concerns such as the realism of the data and the impact on student outcomes. This paper will review the history and several current examples of virtual experimentation, including the author's own experience developing a virtual refrigeration experiment. Learning objectives for laboratory courses defined by the ABET/Sloan colloquy will be used to evaluate the potential impact of converting several existing physical experiments to a virtual or online format. Several conclusions and questions which must be considered when considering virtual experimentation will then be summarized.

I. Introduction

Traditionally engineering laboratory instruction has carried three component goals; instruction on the use of physical equipment and apparatus, use of various statistical and analytical methods to interpret data, and demonstration of fundamental engineering principles. Along with these goals, and their various sub-goals, there are the objectives of improving technical communication and teamwork. In recent years computer based data acquisition and simulation software has added both flexibility and capability to the engineering experimentation curriculum in achieving these goals. The coupling of numerical simulation and experimentation for demonstration and comparison purposes is widely used. New technologies also allow experiments to be controlled over the Internet in a remote or distance education format. However, the most recent laboratory incarnation, virtual experimentation, is the use of numerical techniques to simulate the entire experimentation process (equipment and data).

Virtual experimentation generates reactions of great enthusiasm and trepidation among engineering educators. Many educators see wide ranging applications of these techniques with advantages in terms of learning pedagogies, equipment costs, and online education. However, there are several well-founded concerns such as the realism of the data and the impact on student outcomes. This paper will review the history and several current examples of virtual experimentation, including the author's own experience. Use of new laboratory objectives will be explored to evaluate possible replacement of experiments with virtual versions. Finally, several challenges to the greater adoption of virtual experimentation will be summarized.

II. A History of Virtual Experimentation

The use of experimental procedures and the role of laboratory courses in the engineering curriculum have a long, yet somewhat controversial, history. From the founding of the first engineering school at West Point in 1802 up to World War II engineering instruction included a healthy amount of laboratory or fieldwork to balance theory. Students were taught not only how to design a product but how to build it from scratch. The publication of the Grinter Report[1] in

1955 marked a shift to the theoretical side of engineering. Due to a combination of issues laboratories started to become prohibitively expensive during the 70's and were further scaled back[2]. In the 80's the pendulum swung back as the, then new, conventional *ABET accreditation* criteria recognized the importance of laboratory techniques with set accreditation requirements. Recent years, however; have seen a combination of events that place the laboratory experience at an evolutionary crossroads. Specifically, the development of ever more complex numerical algorithms and computer hardware, and the movement to outcome based assessment with the *EC2000 criteria*. The EC2000 criteria replaced the more prescriptive conventional requirements with the ability to define your own objectives and methods to achieve them, including in the laboratory.

Computers have been an integral part of engineering since their inception. As they have become more powerful, smaller, cheaper, and easier to use their use within the engineering profession and curriculum has grown. As the power of the computer grew the use of numerical techniques to solve or analyze problems was quickly adopted. The development and promotion of the finite element method (FEM) is perhaps the best-known example of this. The ability to solve complex problems numerically allowed instructors more flexibility in classroom and homework activities. *Simulation* could now be used to analyze the stress in a solid bracket, fluid flow over an airfoil, or even the manufacturing of a three-dimensional part. With continued numerical advances simulation opened the door to *numerical experimentation*. Instead of setting up and performing a laboratory experiment to determine a behavior, a numerical simulation could be performed and the resulting numerical data used in place of experimental data. This is a particularly useful technique in cases where an actual experiment would be difficult, if not impossible, to perform due to cost or technical limitations. However, at this stage the student outcomes centered on data analysis or theory verification with little physical or sensory participation.

At the same time computers were changing the classroom with simulations similar advances were being generated within the laboratory. As computers advanced the capabilities of *data acquisition* systems (DAQ) advanced while their associated costs decreased. The use of a computer to take measurements through the conversion of analog experimental signals to digital information in the computer became a standard experimental technique. However, even before this the instrumentation world was changing with the introduction in 1965 by Hewlett Packard of the universal instrument interface[3]. With the subsequent release of the IEEE-488 standard instruments from various manufacturers were able to "talk", "listen", and "control" each other through the General Purpose Interface Bus (GPIB) format. It quickly became possible for the computer to replace some instruments and control the rest. There followed in the 80's and 90's a widespread awakening to the Internet and an exponential increase in transfer bandwidth and speed that gave birth to *remote instrumentation*. No longer was it necessary to be in the laboratory, or even on the same continent, to take experimental data. Students could access the experimental equipment remotely through their personal computer and Internet connection, perform an experiment and collect data, and never have to leave the dorm room. This was facilitated by software products, such as LabVIEW from National Instruments, which provided new graphical capabilities allowing a user to duplicate the appearance and function of a piece of experimental hardware in the graphical user interface (GUI).

The confluence of these three areas gave instructors 1) the ability to numerically model complex systems realistically, 2) the ability to create interfaces which "felt" real, and 3) the freedom to try new approaches at meeting experimental objectives. The resulting pedagogical approach can be referred to as *virtual experimentation*. While there are various definitions for virtual experimentation the importance of having adequate modeling AND user interface must be appreciated.

III. Examples of Technology Used in Virtual Experimentation

Currently there are examples of virtual experimentation in almost every discipline of science, engineering, and technology as well as numerous areas of the arts and humanities. Virtual experimentation can serve several pedagogical uses including use as a classroom aid, use as a pre-lab exercise, or use as an experiment replacement. Several examples from engineering fields that demonstrate unique elements of virtual experimentation will now be reviewed.

The Massachusetts Institute of Technology (MIT) has been active in several areas related to virtual experimentation. The iLabs project is an excellent example of remote instrumentation and experimentation. Typical experimental equipment from Armfield Ltd. is interfaced through universal serial bus (USB) connections with the LabVIEW software package. Students from around the world are able to perform experiments remotely using the MIT Chemical Engineering labs[4]. Other efforts are aimed at full virtual experimentation. Burrell et al.[5] describes the use and evaluation of a web based virtual experiment designed to replace a conventional "wet lab" in the Chemical Engineering program. A web interface that mimics the actual experimental setup allows students to collect data for a rotameter calibration. While the data is simulated it does include both systematic and random error. In an evaluation study students ranked using the actual equipment as more useful than the virtual representation. However, students ranked the virtual lab as easier to use and the authors concluded that the web-based version could be used for teaching data analysis and report writing.

Another evaluation study comes from Wiesner and Lan[6]. Virtual experiments were created for unit operation processes, such as heat exchangers, by creating a realistic interface in LabVIEW and generating data through mathematical models. Conclusions were based on the results of comprehensive exams and ABET outcome surveys and indicated that students welcomed some simulated experiments but "a totally computer-based unit operations laboratory would not be welcome". The authors concluded that the computer-based and physical experiments complement each other.

Besides looking at specific equipment, some researchers have explored simulating laboratory environments. Mosterman et al.[7] describe a virtual system designed with Virtual Basic which mimicked actual experiments in the electronics laboratory. The environment was structured in a bread boarding fashion that allowed eight different experiments to be performed. Students were expected to perform both the actual and virtual experiments. Use of the virtual experiments was found to decrease significantly the amount of time to perform the physical experiment. There were also indications of greater student comprehension and satisfaction.

Finally, an excellent example of virtual experimentation under development is described by Chaturvedi et al.[8]. The experiments come from the thermal-fluids laboratory and deal with flow in a venturi and flow around a cylinder in a wind tunnel. This effort includes two critical advances for virtual experimentation. First, the experiments are placed within a virtual reality laboratory that gives the student a more accurate sensory perception of the laboratory setting. Second, the experimental data is generated with the commercial computational fluid dynamics (CFD) package Fluent while the interfacing is performed with LabVIEW and Macromedia Flash. This coupling of program capabilities, particularly with regard to the use of Fluent for computing data, takes the simulated experience to a new level of sophistication and capability.

III. Virtual Experimentation in the Online Course Arena

One of the biggest motivations toward the development of virtual experimentation is online or distance education. With several institutions now offering entire degree programs online[9] the question of how to handle the laboratory component becomes problematic. Numerous approaches have been used, including arrangements to use nearby laboratory facilities at other institutions (often community colleges), requiring the student to travel to the home institution for short periods for intensive laboratory instruction, giving the students a kit of equipment to perform experiments at home, and replacing the laboratory with virtual experimentation[10,11]. As more of these programs are at the undergraduate level concerns of satisfying ABET accreditation have been raised. Graduates of accredited programs are expected to have "an ability to design and conduct experiments, as well as analyze and interpret data" as well as be able to "use the techniques, skills and modern engineering tools necessary for engineering practice"[12]. For outcome-based assessment (EC2000) the objectives must be known and understood before they can be evaluated. Therefore, in 2002 a colloquy was organized by ABET and funded by the Sloan Foundation to determine educational objectives for laboratories which could be used to evaluate distance programs[2].

The objectives span cognitive knowledge, manipulation of apparatus, sensory awareness, and behavior[2]. These objectives are reproduced and used in Table 3. They allow instructors to better define a course's or experiment's purpose and evaluate their success. However, ABET has been clear on the point that these are not accreditation criteria and that the board makes no policy on simulated experiments. Rather ABET is concerned with whatever method best fulfills the specified outcomes[2,13].

V. Examination of Virtual Experimentation Use for an Existing Experiment

At Minnesota State University Mankato (MSU) mechanical engineering students are required to take a typical experimentation course dealing with the thermo-fluids area. During the Fall 2004 semester students in this senior level experimentation course (ME436 Experimentation II) were asked "Which (if any) experiments would benefit from the use of a simulation program which would allow you to try 'virtual experiments' prior to handling the actual equipment?" Out of sixteen experiments that they had performed that semester (Table 1) four experiments ranked almost equal for this question. They were the Refrigeration, Temperature Measurement, Calorimetry, and Wind Tunnel experiments (Table 2).

Table 1: Experiments for the ME436 Experimentation II course and the student responses for which experiments would benefit from the use of a simulation or virtual experiment program.

Experiment Topic	**# of responses**
Temperature Measurements	**4**
Pressure Measurements	0
Flowrate Measurements	1
Measurement of heating values	**4**
Head loss is piping systems	1
Hydrostatic force on immersed bodies	0
Momentum balance	0
Conduction in solids	0
Internal combustion engine	3
Drag and lift measurement	**4**
Free convection experiment	0
Heat exchanger performance	1
Centrifugal fan experiment	0
Flow through a nozzle	2
Convective heat transfer in pipes	0
Vapor compression refrigeration	**6**

Table 2: Brief experimental descriptions for the top four student selections from Table 1.

Temperature Measurements Students will calibrate several thermometers in a water bath to determine linearity and hysteresis. The effect of reference junctions and added resistance on thermocouple circuits, as well as resistance change with temperature for a RTD will be examined. Students will acquaint themselves with the operation of radiation thermometers (pyrometers).
Measurement of Heating Values (Calorimetry) Students will apply the principles of thermodynamics to the measurement of heating values for fuels. Procedures for both liquid/solid and gaseous fuels will utilized and results compared to standardized values.
Drag and Lift Measurement (Wind Tunnel) Students will acquire experience with wind tunnel testing. Drag coefficients for several objects will be experimentally determined and compared to the tabulated values. Students will investigate the effects of angle of attack on lift and drag coefficients for a NACA airfoil and determine the angle for airfoil stalling.
Vapor Compression Refrigeration Students will become familiar with the operation of an actual refrigeration system. The relationships between key variables in the refrigeration cycle will be explored. A coefficient of performance will be experimentally determined and compared to theoretical values for an ideal cycle.

To examine how the laboratory objectives referenced in section IV might be used the Refrigeration experiment was explored for conversion to virtual experimentation. In this experiment students analyze the performance of an actual vapor compression refrigerator. The students use an experimental workbench based on a R-134a refrigeration cycle (Figure 1). Power to the compressor is supplied by a 3 hp three-phase electric motor powered by a frequency controller. A load cell on the motor allows students to determine the torque. In order to simulate a refrigeration load an electric heater is connected to the evaporator and controlled by a Variac power source. Heat is rejected from the system to a cooling water line through a coaxial heat exchanger. The voltage and current from the Variac, as well as the temperatures and pressures around the cycle are all measured and indicated on digital readouts. The refrigerant and cooling water flowrates are measured with rotameters. The primary goal for this experiment is to demonstrate basic thermodynamic principles and assumptions.

This experiment has several safety and operation concerns that make it very time consuming during the laboratory. The nonlinear and transient response of the system to user control makes it difficult for the students to initially operate, at least within safety margins. While exposure to this nonlinear nature is very educational for the students the amount of time taken to get a "feel" for the system limits what can be accomplished experimentally. In addition, the previous apparatus used for this experiment experienced a catastrophic failure when the students used it improperly, making safety and supervision during this learning phase a primary concern. Through a MSU Presidential Teaching Scholar Fellowship research was done to create a computer simulation of this experiment that mimicked the physical operation of the equipment with realistic data outputs (Figure 2). The intention was to use this as a pre-lab exercise to familiarize students with the equipment operation and allow them to get a better feel for variable relations prior to using the actual equipment.

The simulation is being developed within the LabVIEW environment produced by National Instruments. This offers advantages in terms of user interface design and greater integration of LabVIEW within the course. The program will be downloadable and can be executed through the LabVIEW Player. This will eliminate the need for students to have their own copy of LabVIEW and will allow for more dynamic updating by the instructor (i.e. the files are downloaded each time the students use the software, not downloaded as a static executable). However, to date the experiment simulation has not been used by a full class. Enforcing the fidelity to real data places several numerical constraints on the program. Full agreement between data and model is still being resolved[14].

It has been suggested by some faculty that this experiment could be converted to a remote instrumentation or virtual format. In order to explore this option from a pedagogical point of view the experimental objectives were determined based on the ABET/Sloan colloquy and then the ability to accomplish these objectives with a physical lab versus a virtual lab were predicted by using a high, medium, or low ranking (Table 3).

Table 3: Comparison of instructional objectives based on the ABET/Sloan colloquy for the refrigeration experiment.

Objective	Physical Lab	Virtual Lab
1) Instrumentation	High	High
2) Models	High	High
3) Experiment	Low	Low
4) Data Analysis	High	High
5) Design	N/A	N/A
6) Learn from Failure	Medium	Medium
7) Creativity	N/A	N/A
8) Psychomotor	Medium	Medium
9) Safety	High	Low
10) Communication	High	High
11) Teamwork	High	Low
12) Ethics in the Lab	N/A	N/A
13) Sensory Awareness	Medium	Low

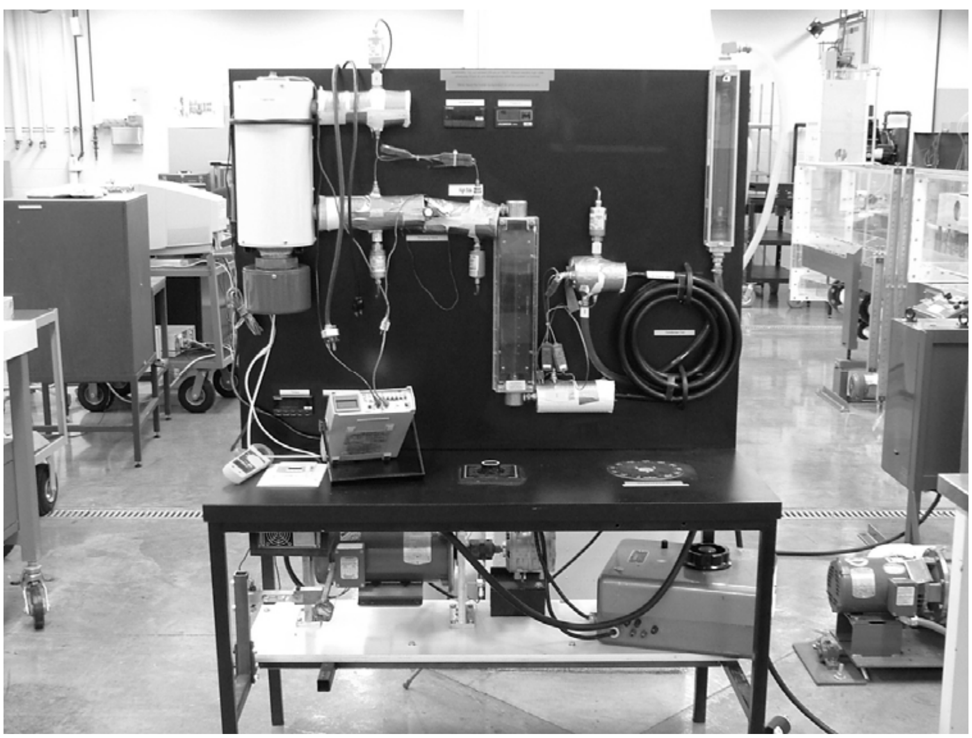

Figure 1: Experimental apparatus used for the refrigeration experiment.

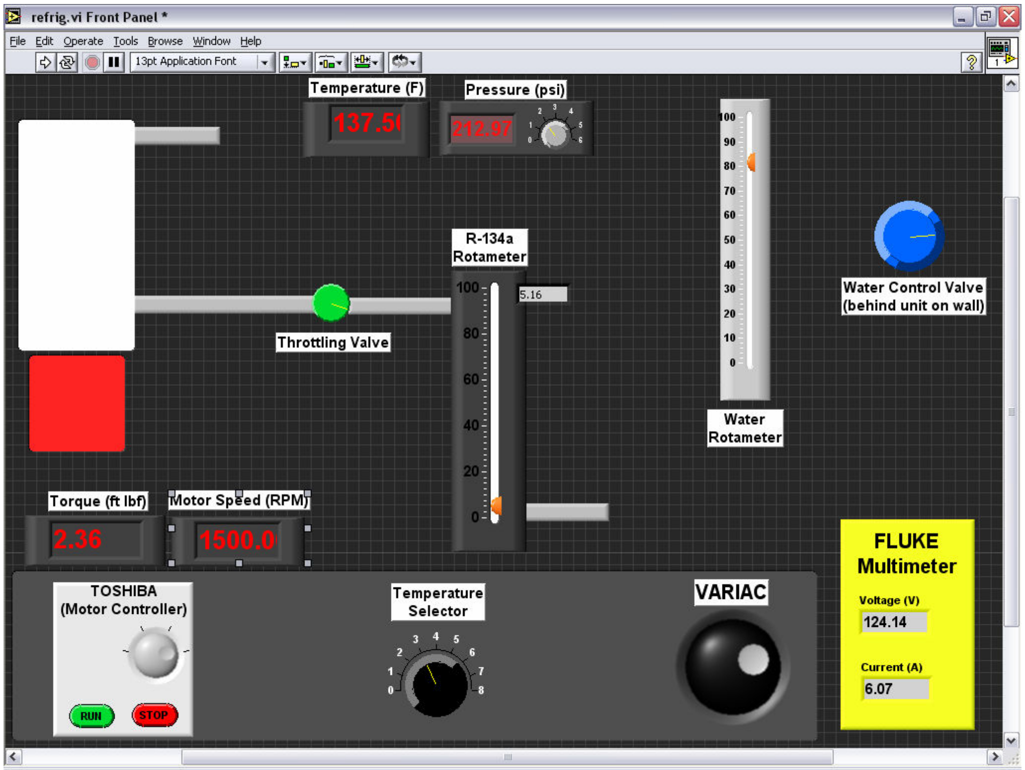

Figure 2: Virtual experiment created to reproduce the data and interface of the refrigeration experiment.

The first objective deals with applying appropriate instrumentation to make measurements. While this experiment involves taking numerous measurements there is limited interaction required from the student since all the transducers are already installed. It was determined that within the framework of this experiment reading a simulated digital readout bore no difference from reading a real digital readout. Similarly, since the equipment is intended to function properly and the students would not be allowed to repair a failure if one occurred, due to safety reasons, there is minimal difference for objectives 3 and 6. Objective 8 was more ambiguous. However, operation of the physical experiment is conducted through simple knobs and one valve. Since the virtual interface was designed to function kinesthetically in the same manner the physical and virtual lab were deemed to be equal at a medium ranking. With regard to testing theoretical models, analyzing data and communicating the results (Objectives 2, 4 and 10) there is no impact as these activities are generally performed outside the laboratory. Naturally a prerequisite to each of these objectives is accurate numerical modeling resulting in realistic results.

Objective 9 is very important for the physical lab. There are several safety issues including rotating machinery and an explosion hazard with the evaporator (if pressure exceeds safety limits). While performing the experiment in a virtual manner does eliminate the danger to the student it does not provide experience to the student in avoiding danger. Therefore, the virtual ranking of low lags the physical ranking of high. Similarly, teamwork is a major component of this, and most, experiments. While there are some methods to promote group work within a virtual setting it was determined that this experiment, as simulated, provided little in the way of teamwork. Objective 13 required some additional consideration. The existing physical lab requires sensory awareness of the controls and indicators. To a large extent this experience has been duplicated through the capabilities of the LabVIEW interface. However, the experiment also requires an awareness of certain equipment characteristics such as the pitch of the electric motor and refrigerant vapor bubbles that can be seen in the rotameter. Currently these factors are not included in the simulation, although the capability exists. Sensory awareness (Objective 13) is, therefore, rated at a low for the virtual lab.

What can be concluded from Table 1? The majority of instructional objectives are met at the same level with the virtual lab. However, three objectives ranked lower. Considering that the primary objective (i.e. the main reason for its existence) for the refrigeration lab is realizing the differences between theory and reality (Objective 2) these differences can be accepted, particularly when coverage of these objectives (9, 11, and 13) in other experiments is considered. Used to replace the physical experiment the virtual experiment would be acceptable. However, used as a pre-lab exercise in conjunction with the physical experiment the virtual experiment is ideal.

Following a similar procedure the other three experiments suggested by the students can be evaluated for replacement or supplement by virtual experimentation. The Wind Tunnel experiment ranks very similarly to the Refrigeration experiment and would be suitable for replacement or supplement with a pre-lab exercise. This experiment is actually better suited as the physical experiment already uses LabVIEW for data acquisition so an exact replica of this portion could be made. The Calorimetry experiment has minimal hands-on instrumentation that cannot be simulated. The experiment does, however; have a large safety component (Objective 9). While Objective 2 could still be considered the primary objective, Objective 9 (safety) is a strong secondary objective. Therefore, this experiment would be difficult to replace by a virtual experiment although a pre-lab format may still be possible. Similarly, the Temperature Measurement experiment has Objective 1 (instrumentation) as its primary objective. Due to the largely kinesthetic nature of these instrumentation methods (i.e. thermocouple creation and connections) it would not be possible to replace this experiment in its current objective form.

VI. Challenges of Using Virtual Experimentation

A conclusion that can be drawn from the literature and the initial research into implementing virtual experiments is that several challenges remain to be addressed.

Objectives – The development and use of the laboratory objectives is a good first step, but it is just the beginning of fully understanding how to use virtual experimentation. Some objectives carry more weight than others. How different objectives, experiments, and even courses relate to each other must be taken into account to decide what the primary purpose of each experiment is. If a primary objective is not satisfied by the virtual experiment can the objective be addressed elsewhere?

Fidelity – Technology now allows many new ways to create virtual experiences. However, achieving full fidelity to physical operation or realistic modeling can be quite challenging and time consuming. What level of fidelity to the physical experiment is needed to satisfy the required objectives? Is this level of fidelity achievable with existing technology and at what cost?

Student perception – Several of the referenced studies showed students thought the virtual experiment was easier or that it saved time in the actual lab, however; several reported that students still preferred a real lab. The source of this preference could reveal important characteristics of the experiential learning process. For instance, is there a valid learning need which is not fulfilled by the virtual experiments or do students have a preconception that real hands-on work is necessary? Most likely it is a little of both but this remains to been fully established.

VII. Conclusions

Advances in technology and moves toward more distance or online learning imply a busy future for virtual experimentation. If used properly virtual experimentation provides advantages in terms of pedagogical approach, cost, and access to experimental equipment. However, use of virtual experimentation must be carefully considered in terms of the laboratory objectives sought. For large-scale use this examination may involve a curriculum wide assessment. Depending on the application and the objectives the time and technology required to achieve the proper learning environment may also be prohibitive. Lastly, student perceptions of virtual experimentation appear to be more complex than currently understood and should be further researched.

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