AC 2012-3412: IMPLEMENTATION AND ASSESSMENT OF A VIRTUAL REALITY EXPERIMENT IN THE UNDERGRADUATE THEMO-FLUIDS LABORATORY

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Implementation and Assessment of Virtual Reality Experiment in the Undergraduate Thermo-fluids laboratory

Abstract

Results are presented from an NSF supported project that is geared towards advancing the development and use of virtual reality (VR) laboratories, designed to emulate the learning environment of physical laboratories. As part of this project, an experiment in the undergraduate thermo-fluids laboratory course titled “Jet Impact Force” was transformed into a 3-D virtual reality experiment using the widely used MAYA^R and VIRTOOLS ^{R} software. In order to facilitate students’ interactions with the newly created 3-D interactive, immersive and stereoscopic virtual laboratory environment, the human computer interfaces (HCI) were programmed and incorporated in the simulation software. Two immersion levels were included in the VR experiment to assess their impact on student learning. The first one namely the desk-top virtual reality (DTVR) used a computer and a 3-D TV for display while the CAVE virtual reality (CVR) employed a computer in conjunction with a three-wall CAVE (acronym for Cave Automatic Virtual Environment) for visualizing the simulation. The above said VR experiment was embedded in the thermo-fluids laboratory course in the mechanical engineering curriculum at Old Dominion University (ODU) so that it could be used in the supplementation mode for the pre-lab practice sessions prior to the physical experiment sessions. To test the efficacy of this supplementation pedagogy for enhancement of student learning, both quantitative (quiz) as well as qualitative (direct observation and student survey) assessment instruments were used. Of the three objectives set for this study two, namely the development and implementation of VR experiment and the assessment of impact of immersion levels on student learning were fully achieved. Assessment results also showed that the “CVR” module resulted in a higher level of student learning when compared with the “DTVR” module. The third objective, namely the assessment of the VR experiment in enhancing student learning in the supplementation mode was met only partially since the quantitative and qualitative assessments produced divergent results. The statistical analysis of the quiz scores of the “experimental” group, consisting of students who used the VR experiment for supplementation, and the “control” group (without supplementation) showed that the supplementation produced improvements in student learning that were statistically insignificant. In contrast the direct observation of both the “experimental” and the “control” groups during the physical experiment pointed to student learning gains for the “experimental” group. Student surveys showed generally positive disposition of students towards the newly introduced VR experiment.

Introduction

Computer-based immersive visualization in recent years has become an important catalyst in the development of virtual reality (VR) laboratories that hold considerable promise for becoming a powerful teaching and learning tool in engineering education. The fiscal realities of the shrinking resources coupled with escalating cost of modernizing engineering laboratories have prompted educators to investigate innovative ways in which VR labs can be used for laboratory instruction. Maturation of digital technologies and their sharply declining costs has put cyberinfrastructure applications such as virtual reality-based undergraduate engineering labs within the reach of many cash strapped engineering institutions. Although virtual reality labs can potentially be used in the several educational settings, one application explored in this paper for which VR labs are eminently suited involves using them for supplementation of physical laboratories. Students in this modality use the VR lab for pre-lab practice sessions prior to conducting a physical experiment. This application is expected to enhance students' knowledge of physical experiment, pertaining to objectives, procedure and data collection. Over the years it has been authors' experience that many students in laboratory courses come to physical lab sessions without adequate preparation, often not knowing even the main objective of the experiment. This is despite instructions to students to review the details of experiments from the lab book provided to all students in the course. Due to their highly visual and immersive nature VR labs are expected to remedy this situation and improve students' preparedness for the physical lab sessions. Students' exposure to an experiment in both physical and virtual domains is expected to reinforce students' learning. Since majority of current engineering students are technology savvy visual learners [1], the highly visual nature of the VR labs is also expected to make students' lab experience engaging and exciting. There is considerable published literature that documents student learning gains from the supplementation of classroom instruction with the modern technology tools [2]. The authors of the present paper have also demonstrated that supplementation of the engineering lecture and lab courses with web-based visualization and simulation modules produces student learning gains [3-6], a conclusion also reached by others [7-9] and highlighted in the NSF's Fostering Learning in the Networked World [10].

Literature review

Engineering is an applied field that requires hands-on skills. The current educational practice is to provide hands-on experience primarily through bench-type experiments in physical laboratories. In order to gain acceptance as a tool for laboratory instruction a virtual experiment at the very last must include: (a) hands-on activities (interactivity), and (b) a realistic simulation of the experiment in a laboratory like environment (immersion). It should be noted that bench-type physical experiments have drawbacks of high capital cost, limited (one time) exposure to experiments and limited students' interaction with experiments due to large student group sizes. As a result student learning does not always reach expected levels [11-12]. Bourne has stated that student learning achieved through online virtual experiments may be comparable to learning achieved through bench-type physical experiments [13]. The virtual reality experiments do not have some of the drawbacks of bench-type experiments mentioned earlier. However, creation of life-like virtual reality laboratories rivaling physical laboratories in providing students hands-on experience still remains a daunting task due to technical as well as perceptual challenges. Application of virtual labs for providing hands-on experience in laboratory courses has lagged because engineering professors generally view physical laboratories as the primary means of providing students the hands-on experience for engineering practice. As a result many of them are averse to using simulated virtual experiments. Students may also prefer using physical labs instead of virtual labs [14] due to equating of the term "virtual" with the term "non-real". However, it should be pointed out that the definition of "hands-on experience" itself is changing as the industry is increasingly relying on computer simulations and virtual reality [15], and as a result the term hands-on experience does not necessarily imply dealing only with physical hardware. Instead "hands-on experience" can also be realized in the virtual domain, using computers, the internet and virtual reality tools. Some industry leaders as well as education leaders have suggested that computer modeling and visualization should be used in the interactive mode to promote students' hands-on skills now being demanded by industry [16-17].

Virtual laboratories can be broadly classified into four categories [18], namely recreative (simulation without interactivity), interactive, immersive/interactive, and collaborative. At the bottom of the hierarchy shown in Fig.1 are the recreative virtual labs that are merely a simulation of a physical phenomenon or an experiment, visualized on a computer screen. These simulations are used primarily for demonstration of complex physical phenomena. Ability to interact with the simulation is not provided to users who just view the simulated phenomenon passively. Interactive virtual labs attempt to replicate physical experiment on a computer screen generally in two-dimensions. They provide the interactivity feature that allows users to input data and receive responses from a simulation which changes dynamically as a result of changing input setting such as opening or closing of a valve in a pipeline. A large percentage of virtual labs reported in the literature belong to this category [19-24], spanning practically every field of engineering. Immersive interactive virtual labs represent improvement over interactive virtual labs since they provide both interactivity as well as immersion, in three-dimensions. The 3-D immersion gives users a sense of presence in a simulated laboratory environment, mimicking what one would experience during a physical experiment in a laboratory. Investigators in the fields of science, medicine and engineering have developed a number of immersive experiments (in the virtual domain) for educational purposes [25-29]. Web-based collaborative experiments use online collaboration of computers to allow users to: a) perform experiment as a team whose members are geographically distributed, or b) share real time data in scientific experiment which is being conducted at a central location. These labs have also been called collaboratories [30]. Application of these online collaborative labs to engineering education is still in its infancy. However, their potential for use in distance engineering education programs is substantial and needs to be explored. The web-based game technology and social network media such as "Second life" have advanced rapidly in recent years to allow geographically distributed users to either play games collaboratively or to enable their avatars to interact with one another on the web. The Collaborative Web Technologies (CWT) have evolved to the extent that they can be also applied to develop collaborative engineering laboratories for web-based engineering programs.

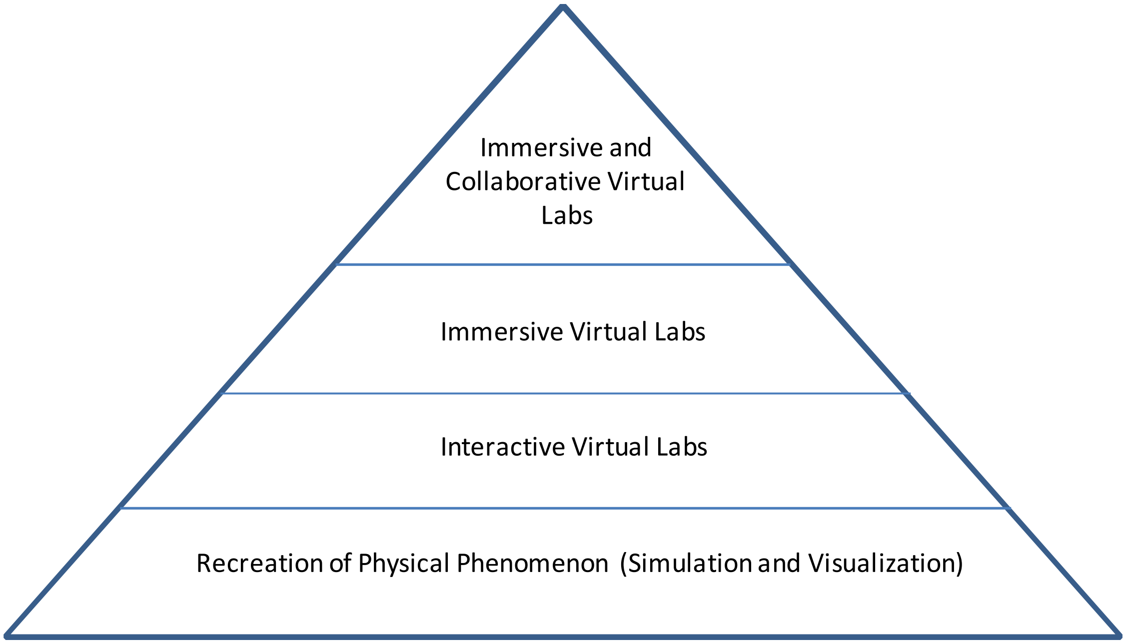


Figure1. Classification of virtual laboratories

Objectives and Scope of the Present Work

The literature review of virtual labs presented in the previous section indicates that the state of the art has advanced considerably in recent years. However despite recent developments, the research in this field has yet to be translated into strategies that would make virtual reality laboratories an integral part of engineering education. The present study is a step in that direction. The overarching goal of this study is to advance the development and use of virtual reality laboratories that will closely emulate the learning environment of physical engineering laboratories. In this pilot study, a 3-D virtual reality experiment emulating a physical experiment titled “Jet Impact Force” in the thermo-fluids laboratory course in the mechanical engineering curriculum has been developed, implemented and assessed. The VR experiment is used in the supplementation mode for pre-lab practice sessions to help prepare students for the physical experiment. Two virtual reality environments with different level of immersion have been developed and assessed. In the desk-top virtual reality (DTVR), a desk-top computer is coupled with a 3-D TV while in the CAVE virtual reality (CVR), a computer is coupled with a three wall “CAVE” to create laboratory like 3-D immersive environments for conducting virtual pre-lab practice sessions. Both virtual reality versions were implemented and assessed to gage student learning gain, due to pre-lab practice sessions. The assessment section in this paper presents the “experimental design” and the statistical analysis of collected data to determine the impact of this VR experiment on student learning.

In summary the main goals of this study are:

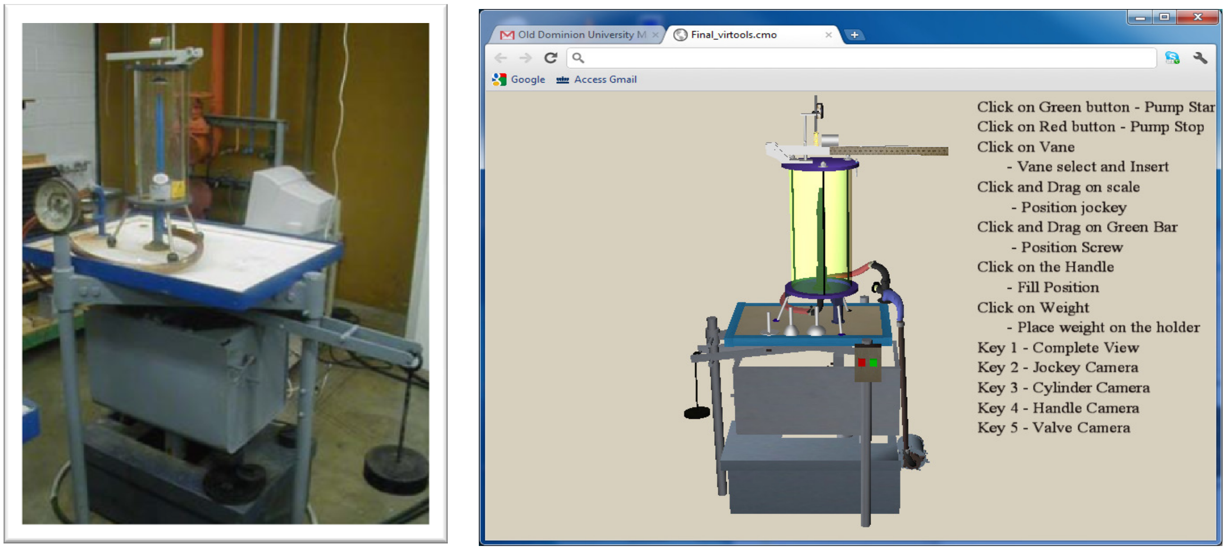
(a) Development and implementation of a virtual reality experiment in the thermo-fluids laboratory course,
(b) Quantitative as well as qualitative assessment of the VR experiment as a supplementation tool in the lab course, and
(c) Assessment of impact of different levels of immersion ("DTVR" vs. "CVR") on student learning.

Broader Impacts on Engineering Education

The broader impacts of this study relate to educational process in higher education. The project is currently geared towards assessment of the virtual reality experiment used in the practice runs prior to physical laboratory sessions. Pedagogical results and lessons learned from this project are expected to advance the application of VR labs to other educational settings. The VR lab development effort and its effectiveness in enhancing student learning is expected to pave foundation for development of hybrid labs consisting of an optimal mix of physical and virtual experiments. Due to their cost effectiveness, inherent flexibility and the ability to provide hands-on experience in both physical and virtual domains, the hybrid labs have the potential of revitalizing engineering education infrastructure for the new globally competitive knowledge-based economy. In the other educational setting namely distance learning, virtual reality experiments of the type discussed here are expected to become building blocks for development of virtual reality labs enabling more advanced distance learning web-based programs that would reach a more diverse non-traditional student base. It is interesting to note that Gross has identified difficulty in providing laboratory experience on the web as the principal reason for paucity of distance learning undergraduate programs [31]. This project also advances the learning environment in engineering schools through incorporation of exciting and user friendly modern technology-based instructional tools, such as VR labs, that are more in tune with current engineering students' visual learning style [1] in the modern digital age.

Thermo-fluids Laboratory Experiment

In this junior level laboratory (ME 305), the "Jet Impact Force on Vanes" has been chosen for the physical-to-virtual reality experiment transformation. The experiment shown in Fig. 2 involves determination of jet impact force arising from reversal of a jet after hitting a vane. The equation $F = C\dot{m}^n$ represents the relationship between force (F), mass flow rate ($\dot{m}$) and type of vane (C). Water from a storage tank is pumped through a nozzle to create a jet directed towards a vane mounted on a pivoted arm on which a known jockey weight can slide. The deflected beam due to the impact of the jet is returned to its balanced (horizontal) position by sliding a jokey weight on the spring loaded pivoted arm. The balance position is achieved when the moment of the jokey weight about the pivot point equals the moment of the jet force (F). This results in a reading of jokey weight displacement L in mm, and determination of force F. The mass flow rate ($\dot{m}$) is measured by determining the time required to collect a given mass of water in a tank. The water collection tank is also mounted on one end of another pivoted arm whose opposite end carries a weight holder. First the collection tank is filled with water until the collection tank balances the weight holder. At that point an additional known weight is mounted on the weight holder to cause the pivoted arm to go out of balance. The time required to fill in additional water so that the pivoted arm is returned to its balance position is recorded. The ratio of additional mass of collected water and time required gives the mass flow rate. The experiment is then repeated for several flow rates and two other types of vanes. From recorded values of F and $\dot{m}$ data, values of C and n are determined. A 3-D virtual reality model of this experiment has been developed and embedded in the ME 305 laboratory course (Fig. 2).



Click on Green button - Pump Star
Click on Red button - Pump Stop
Click on Vane
    - Vane select and Insert
Click and Drag on scale
    - Position jockey
Click and Drag on Green Bar
    - Position Screw
Click on the Handle
    - Fill Position
Click on Weight
    - Place weight on the holder
Key 1 - Complete View
Key 2 - Jockey Camera
Key 3 - Cylinder Camera
Key 4 - Handle Camera
Key 5 - Valve Camera

Physical Set-up

3-D Virtual Reality Model

Figure 2: Physical set-up and the 3-D virtual reality experiment

Mapping of Physical Experiment into a Virtual Reality Experiment

The physical to virtual domain mapping process is shown in Fig. 3. The first step in the mapping process attempts to capture the essence of the physical experiment by preserving geometrical details and by ensuring that student generated activities follow a sequence similar to the physical experiment. Minimally, the characteristics to be replicated in the virtual domain should be able to demonstrate the physics of the experiment. These steps are followed by modeling and simulation of the phenomenon and identification of the method of data generation for recreation of the phenomenon in the virtual domain. Since perfect (one-to-one) mapping of a physical phenomenon into virtual domain is not possible, certain activities in an experiment may have to be modeled and simulated. In present study empirical data was used to create all student generated activities in the virtual domain. Data outside of expected activities in an experiment, such as fix a connection or touch the fluid to get a kinesthetic internal calibration for viscosity, were not considered. The second step involves creating a static 3-D CAD model of the physical set-up using the MAYA^{R} software. This provides the user the ability to view the experimental set-up from any perspective by rotating the virtual model on a computer screen. This is analogous to a student viewing a non-operating physical system by going around it. The third step involves making the 3-D virtual model interactive as well as stereoscopic, using the software $VIRTOOLS^R$. After completion of this step students can interact with the software using a keyboard or a mouse and observe the animation on a 3-D computer monitor screen. Creating two stereoscopic images of the virtual model, one each for the left eye and the right eye, lays the foundation for increased immersion at later stages. In the fourth step hand-held interface devices such as a game controller is programmed and evaluated for their suitability for serving as the interface between user and the VR software for both desk-top as well as "CAVE" immersive environments. This step results in a compelling combination of virtual reality software and associated interfacial devices which enables students to experience a high level of immersion while performing various tasks related to experiment.

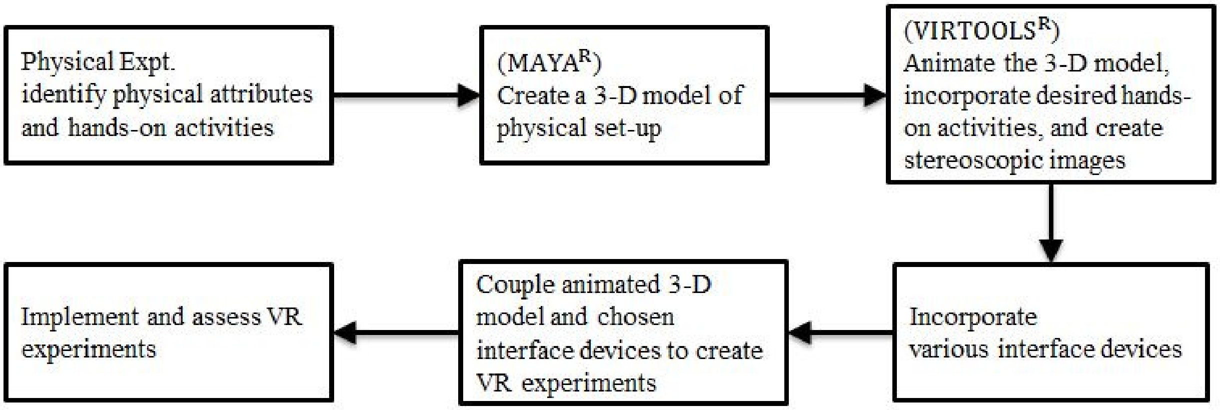


Figure 3: Steps in physical-to-virtual mapping process

Immersion

The "Jet Impact Force" experiment has been implemented for two levels of immersion. In the desk-top virtual reality (DTVR) implementation, a 3-D TV display (screen size 55") is connected to a desk-top computer for running the simulation software and using 3-D glasses to help students visualize the virtual 3-D model in a stereoscopic view. The human-computer interfaces (HCI) have been created to facilitate student interaction with the DTVR system through employment of a key board and mouse, and a game controller. Students have used a game controller during the pre-lab practice sessions to interact with the simulation software. It should be emphasized that a 3-D TV display represents a one plane or one wall projection system. In contrast a "CAVE" represents a higher level immersive virtual reality environment where digital projectors are directed to three, four, five or six walls of a room sized cube. In the present case, a three wall "CAVE" projection system located in the Engineering and Computational Sciences Building (ECSB) at the Old Dominion University campus was used by students for the pre-lab practice sessions. The same HCI namely a game controller was used by students to interact with the simulation projected on the "CAVE" walls. Due to its intrinsic nature, a "CAVE" provides a higher level of immersion giving a feeling to students as if they are part of a laboratory environment. In order to accomplish this, other lab equipment's were also incorporated in the simulation so that the "Jet Impact Force" experiment can be viewed as part of a simulated laboratory environment.

Quantitative and Qualitative Assessment

Overview and Hypothesis used in Assessment

MAE 305 Thermo-Fluids Lab, Fall semester, 2011 course had three sections and was used for implementation and assessment of the VR experiment. Each section is then partitioned into three student groups, each with five or six students that rotate over a number of laboratory experiments per week. One particular laboratory experiment, “Jet Impact Force” in each section was implemented with three different learning settings – (1) physical experiment only, (2) prior desktop virtual reality (DTVR) practice and posterior physical experiment, and (3) prior CAVE virtual reality (CVR) practice and posterior physical experiment – to investigate corresponding students learning effectiveness achieved through these modules. Measures of evaluating students learning effectiveness consist of both quantitative (quiz scores) and qualitative (survey and direct observation) outcomes. Since current engineering students at Old Dominion University are attuned to interactive visualization due to their familiarity with computers and video gaming, the hypothesis is that either “DTVR” or “CVR” would supplement and enhance student learning above and beyond levels achieved through conventional physical experiment only mode.

Assessment Experimental Design

The Intact Group method was used to assess the impact of different modules on student learning. [32] Among three learning settings, “physical experiment only” mode was set as a “control” group, and the remaining two “DTVR” and “CAVE” modules were set as “experimental” treatment groups. The “control” group consisted of students who did not have access to either “DTVR” or “CAVE” modules. Learning of the subject matter in the “control” group prior to the physical experiment was achieved mainly through the lab book provided to all students. Students in the “experimental” groups supplemented their learning with “DTVR” or “CAVE” modules. A pre-assessment survey containing self-reported questions on student learning style (i.e., self-learner, group-learner, interactive-learner, structured-learner, etc.) and computer literacy (i.e., intermediated, advanced, level of daily utilization of computer and typical utilization category, etc.) was conducted. Collected data on student learning style and level of computer literacy were used to balance each group with similar proportion of students in each learning style and computer literacy level so that assessment can be performed unskewed from particular learning style and computer literacy level bias.

Quantitative Assessment – Statistical Experimental Design

To objectively determine whether the implemented modules had contributed to enhanced students' learning compared to the pre-implementation condition, i.e., was there any difference in the mean scores of quizzes under “Without Module” (=control group) and “With Module”

(=experimental group) settings, course outcomes were collected and statistically analyzed. Instead of simply comparing the arithmetic means of outcomes and subsequent visual display of graphs, which is limited to the descriptive statistics on per-event sample data and seldom provides any population-level intrinsicality and reproducibility (=true module effectiveness), standard statistical analysis methodology in form of experimental designs was applied to make an objective and correct inference about the module effectiveness.

As a preliminary step, quantitative student outcome dataset, quiz scores, from three groups (one "control/Without Module" and two "experimental/With Module") were evaluated by using a median-based one-way, pairwise nonparametric statistics, Wilcoxon Rank Sum statistics [33] to test the hypotheses on central tendency and dispersion at 95% level of confidence ($\alpha = 0.05$).

H_0: $\tilde{\mu}$ [Quiz{Without Module}] = $\tilde{\mu}$ [Course Outcomes{With Module}]

H_a: $\tilde{\mu}$ [Course Outcomes{Without Module}] < $\tilde{\mu}$ [Course Outcomes{With Module}]

or > $\tilde{\mu}$ [Course Outcomes{With Module}]

At 95% confidence level, if Wilcoxon Rank Sum *p*-value is less than 0.05, then a conclusion can be made that there is a significant difference between the central tendency of the course outcome/quiz score at their population levels, or mean scores of the student performance under "Without Module" (=control) and "With Module" (=experimental) settings are different

To compare contribution of "Without Module" (=control) and "With Module" (=experimental) settings toward enhancing students' learning effectiveness, standard RCB (Randomized Complete Block) design [34] is used to construct control treatment levels ("Without Module" and "With Module). All analyses are conducted by using SAS/STAT Statistical Analysis System [35] available on the ODU LIONS SunGRID HPC computing cluster. Statistical analysis was performed on quiz scores from three groups (one "control/Without Module" and two "DTVR" and "CAVE" experimental/With Module") using the Statistical Analysis System (SAS). To ensure objectivity, a blinded analysis was conducted without identifying "control", "DTVR" and "CAVE" groups. Instead, generic group identifications of "Batch 1," "Batch 2"and"Batch 3" were used during the analysis.

The conclusions pertaining to module effectiveness (in form of quiz score only) in enhancing student learning are summarized in Table 1. As reported in the table, the difference in module effectiveness (in form of quiz score only) between "Batch 1" and "Batch 2" is statistically insignificant, indicating the magnitudes of student learning enhancement achieved by "Batch 1" and "Batch 2"modules for the Jet Impact Force experiment in MAE 305 Thermo-Fluids Lab, Fall semester, 2011 were equivalent. The difference in module effectiveness (in form of quiz score) between "Batch 1" and "Batch 3" is also statistically insignificant, indicating the magnitudes of student learning enhancement achieved by “Batch 1” and “Batch 3”modules as being equivalent.

However, the difference in module effectiveness (in form of quiz score only) between “Batch 2” and “Batch 3” is statistically significant, indicating the magnitudes of student learning enhancement achieved by “Batch 3” is significantly greater that by “Batch 2”module. Since the central tendency of “Batch 1” is statistically equal to those of “Batch 2” and “Batch 3” modules, this singular difference between “Batch 2” and “Batch 3” needs to be taken with caution, and further analysis on demographic factors should be conducted before arriving to a final conclusion. It should be also pointed out that this analysis represents student outcomes from only one semester. Additional and composite analyses by using more semester trials would provide more clear and reproducible picture of module effectiveness toward enhancing student learning

Table 1. Test Statistics and *p*-values for Quiz Score Comparison (α=0.05), One-way, Pairwise Nonparametric Wilcoxon Rank Sum Test, Jet Impact Force experiment in MAE 305 Thermo-Fluids Lab, Fall Semester, 2011 (n=39)

	Batch 1 **(Mean score)in percent** **(n=17)**	**Batch 2** **(Mean score)in percent** **(n=17)**	**Batch 3** **(Mean score)in percent** **(n=15)**	***p*-value**	**Remark**
Batch 1 vs. Batch 2	17.8	17.2		0.4375	Not Significant
Batch 1 vs. Batch 3	14.1		19.2	0.0637	Not Significant
Batch 2 vs. Batch 3		13.8	19.5	0.0421	Significant

Qualitative Assessment- Direct Observation

Assessment can be quantitative or qualitative [36]. Both methods have been used in this assessment study. For qualitative assessment, direct observation and survey were conducted on both “control” and “experimental” student groups.

Qualitative direct observations were made on all three groups from each section while conducting the "Jet Impact Force" experiment. Direct observation was made on overall familiarity with the experimental procedure as well as two observatory components of (1) Balancing Jockey Weight over the Beam, and (2) Mass Flow Rate Determination during the experiment based on the Likert scale of 1 to 5 as shown in Table 2. Additional motion and group kinetic data were collected. Time lapse measurement was made for the first trial of the experiment procedure, immediately followed by circling the observed Likert scale (listed in the Table 2) of student familiarity to the observatory component. Rationale is that after first trial, students would become familiarized with procedure regardless of which module (i.e., Physical, "DTVR" and "CAVE") they belong to, and observing effect of such applicable module treatment would become difficult. Rating of "Overall familiarity with the experimental procedure" was made right after the third trial of the experiment. Rationale is that students become quite familiar with the procedure by the third trial and yet the observer would still be able to detect the subtle differences contributed by different treatments. After the third trial, observing effect of such applicable treatments would become difficult.

Table 2. Qualitative Direct Observations,
Jet Impact Force experiment in MAE 305 Thermo-Fluids Lab, Fall Semester, 2011 (n=39)

No clue, does not appear to have any knowledge of the required procedure	Appear recognizing elements of the required procedure with a high level of hesitation and guess	Reasonable understanding of the procedure, with a level of hesitation and guess	Fair understanding of the procedure, with a hint of trial and error to perform the required procedure	No guess or hesitation, fully understand and able to perform the required procedure with certaintlimuRy78
Scale 1	Scale 2	Scale 3	Scale 4	Scale 5

By nature, all students in a group conducting the physical experiment will be involved with varying levels of engagement. Beta students are more "passive" (or mildly aloof in the worst sense) in their involvement level compared to alpha students who are actively involved in observed activities [37]. Non- responsive category refers to students who do not respond at all to the newly introduced treatment. Alpha students are likely to proactively accept and use the new paradigm than Beta students. Thus measuring Alpha-Beta student kinetic would provide an insight on different levels of effectiveness of virtual module to the proactive vs. passive recipients. If the ratio of Alpha students in a group is larger than typical 10-15% composition, it would indicate that the module was effective enough so that a significant Beta to Alpha conversion had occurred before the physical experiment. Thus observing the transition of Beta students into Alpha students during the physical experiment would be a good indicator that virtual module was effective enough to boost Beta students' confidence and facilitate them to become more "active" for the specific physical experiment. The learning mode of Beta students tends to stay "passive" in traditional learning.

During the direct observation, additional comments on group kinetics including Alpha vs. Beta Student interactions were recorded to further understand student response to the virtual modules by capturing followings;

i) Ratio of Alpha- vs. Beta-students in the group, i.e., 2 Alpha and 4 Beta, etc.

ii) Level of interaction/discussion between Alpha- vs. Alpha-, Alpha- vs. Beta-, and Beta- vs. Beta-students, i.e., do Beta-students point out/correct procedural mistake(s) made by Alpha-student?

iii) Gradual change, if there is any, in Alpha- vs. Beta-students ratio in the group at the later part of the experiment.

Table 3 summarizes findings from the direct observation. For the "Balancing Jockey Weight over the Beam" observatory component, Likert scales of both "DTVR" and "CAVE" are scored higher than the scale of the "Physical only" group. The same tendency prevailed in the "Mass Flow Rate Determination" observatory component. Measured time lapse data also indicate a similar tendency. Correspondingly, based on Likert scale aggregates, students in the "DTVR" and the "CAVE" modules appeared more familiar with experiment procedures than students in the "Physical only" module. Alpha vs. Beta student group kinetics show that the "DTVR" and the "CAVE" modules in general have more Alpha students in its group composition, implying the number of students familiar with the experiment procedure via "DTVR" or "CAVE" is larger than that of the "Physical only" module. Interaction among group member and the level of involvement were also observed to be higher in the "DTVR" and the "CAVE" modules compared to the "Physical only" module.

Table 3. Summary of Qualitative Direct Observations, Jet Impact Force experiment in MAE 305 Thermo-Fluids Lab, Fall Semester, 2011
(Likert scale 1 to 5 with number one and five signifying “not familiar” and “very familiar,” respectively

(1) Balancing Jockey Weight over the Beam (n=39)

	Likert Scale	Time Lapse (sec)	Group Kinetics	Comments
Physical #1	3	16.3	1 alpha, 3 beta, 2 non-responsive	High hesitation
Physical #2	2	17.2	1 alpha, rest are non-responsive	Not much interest
Physical #3	1	27.5	2 alpha, 3 beta	High hesitation, low interaction among
DTVR #1	4	8.3	No alpha-beta group observed	Good interaction among group members
DTVR #2	4	6.3	No alpha-beta group except one stayed passive	Good interaction among group members
DTVR #3	4	13.0	2 alpha, 3 beta, one stayed passive	High interest in alpha group, good interaction
CAVE #1	4	6.6	3 alpha, 3 beta	Alpha group driven
CAVE #2	4	10.5	1 alpha, 4 beta	Excellent group involvement
CAVE #3	3	22.2	2 alpha, 3 beta,	Group involvement moderate to high

Table 3. (continued) Summary of Qualitative Direct Observations, Jet Impact Force experiment in MAE 305 Thermo-Fluids Lab, Fall Semester, 2011
(Likert scale 1 to 5 with number one and five signifying “not familiar” and “very familiar,” respectively)

(2) Mass Flow Rate Determination (n=39)

	Likert Scale	Time Lapse (sec)	Group Kinetics	Comments
Physical #1	2	19.8	1 alpha, 3 beta, 2 non-responsive	High hesitation
Physical #2	2	29.2	1 alpha, rest are non-responsive	Not much interest
Physical #3	2	32.9	2 alpha, 3 beta	High hesitation, low interaction among
DTVR #1	3	20.9	No alpha-beta group observed	Good interaction among group members
DTVR #2	4	15.7	No alpha-beta group except one stayed passive	Good interaction among group members
DTVR #3	4	20.6	2 alpha, 3 beta, one stayed passive	High interest in alpha group, good interaction
CAVE #1	4	30.3	3 alpha, 3 beta	Alpha group driven
CAVE #2	4	23.2	1 alpha, 4 beta	Excellent group involvement
CAVE #3	2	17.9	2 alpha, 3 beta,	Group involvement moderate to high

Qualitative assessment – Student surveys

At the end of the semester, students in both “control” and “experimental” groups were given a survey form containing a series of questions framed to capture qualitative feedback from students concerning various aspects of the experimental modules namely – (i) effectiveness, (ii) usability and (iii) future applicability. The survey form used the Likert scale 1 to 5 with number one and number five signifying strong disagreement and strong agreement respectively with a posed question. The purpose of this qualitative assessment is two-fold: (a) to gage students perception (positive or negative) concerning the use of “DTVR” and “CAVE” for supplementation of in class learning, and (b) to use students comments and suggestions for further improvement of implemented modules. Table 4 shows the survey results for both “DTVR” and “CAVE” modules in form of average rating for each of the six questions posed in the survey form. The first question pertains to the effectiveness of the modules in preparing students for the actual physical experiment session. Average ratings of 4.21 for the “DTVR” module and 4.08 for the “CAVE” module indicate that students are generally in agreement with the posed question, and consider the modules to be effective in enhancing their understanding of experimental procedure. Students’ responses were generally favorable for all questions except the second question which relates to enhancement of student understanding of theoretical basis for relationship between the jet impact force and mass flow rate.

Table 4: Student Survey Results (n=39)

No.	Questions	Average Rating	
		"DTVR" Group	"CAVE" Group
1	The pre-lab 3D simulation was helpful in understanding activities involved in experimental procedure, and was effective in preparing me for the actual physical experiment session.	4.21	4.08
2	The pre-lab 3D simulation enhanced my understanding of theoretical basis for relationship between the jet impact force and mass flow rate.	3.71	3.15
3	The pre-lab 3D simulation exposed me to information not really available in lab manual.	4.07	3.69
4	The pre-lab 3D simulation was user-friendly	4.00	4.15
5	The time allocated for reviewing the pre-lab 3D simulation was adequate.	4.43	4.31
6	The pre-lab 3D simulation and visual effects, replicated the actual physical experiment well. More visualization modules should be developed for other physical experiments in the laboratory.	4.64	4.00

Conclusions

Three goals were set for this project: (a) development and incorporation of virtual reality experiment in an engineering laboratory course; (b) comparison of impact of various levels of immersion in the VR experiment on student learning and (c) comprehensive assessment of student learning gains due to supplementation of the physical experiment with the two versions of VR experiment. All three goals were achieved either fully or partially, as indicated by quantitative as well as qualitative assessment instruments used in the study. As discussed earlier, the virtual reality experiment was successfully developed and embedded in the thermo-fluids laboratory course during the Fall 2011 semester. The second objective related to assessment of effects of different levels of immersion on student learning and it was also successfully achieved. The quiz results indicated that students using the "CVR" module for pre-lab practice runs learned better compared to students who used the "DTVR" module for practice runs. The student learning gain as measured by the quiz scores was statistically significant, and indicated that the "CVR" module with three wall projection system represented a better learning environment compared to the "DTVR" module.

In order to address the student learning achieved through supplementation of the physical experiment with virtual pre-lab practice sessions (third goal), both quantitative as well as qualitative assessment instruments were used. Analysis of quiz results indicated there was no statistically significant improvement in student learning due to either "DTVR" or "CVR" supplementation as compared to the "control" group. It is interesting to note that the mean quiz score for the "CVR" group increased by about 15 percent over the "control" group mean quiz score. However, the analysis showed that this improvement was statistically insignificant. The "direct observation" assessment did indicate that students who used either the "DTVR" or the "CVR" supplementation: (a) were better prepared for the physical experiment; (b) made fewer mistakes; (c) showed better collaboration among group members and (d) completed key measurement activities in shorter time span as compared to students in the "control" group. The student surveys for the "DTVR" and the "CVR" also corroborated the conclusion in (a). One of the reasons for lack of statistically significant student learning gains, gaged through quiz scores, may possibly be attributed to differences in demographic profiles of students belonging to "control" and "experimental" groups. For instance, differences in cumulative GPA for the two groups would make it difficult to interpret the data for student learning gain. Since demographic data were not available to authors, further investigation should also account for differences in demographic profiles, if any. The author plans to continue to assess the VR experiment in the coming semesters to collect more data and to see if any statistically significant differences in the outcomes are observed. The author would also like to put forth the argument that for assessing the impact of interventions or new treatments in laboratory courses, "direct observation", though a qualitative measure can also be an indicator of the success of new treatments or educational strategies of the type discussed here. This is because the "direct observation" rubric used in this study is a mix of qualitative as well as quantitative measures such as time lapse data that tends to capture the level of students preparedness reasonably well.

In summary, this paper makes contributions in two areas, namely the development of virtual reality labs for engineering laboratory courses and assessment of the pedagogy which involves using the VR experiment for supplementation of physical laboratory experiments. Although ABET outcomes were not directly addressed, one outcome namely "Can use modern engineering techniques, skills and tools necessary for engineering practice?" is relevant and directly related to the project discussed here. Since most engineers use both physical as well as virtual environments in engineering practice, students' exposure to both physical and virtual reality experiments is likely to inculcate in them, the importance of both methods for observing and analyzing an engineering phenomenon.

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