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Evaluation of Virtual Reality Based Learning Materials as a Supplement to the Undergraduate Mechanical Engineering Laboratory Experience*

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Virtual reality offers vast possibilities to enhance the conventional approach for delivering engineering education. The introduction of virtual reality technology into teaching can improve the undergraduate mechanical engineering curriculum by supplementing the traditional learning experience with outside-the-classroom materials. The Center for Aviation and Automotive Technological Education using Virtual E-Schools (CA^{2}VES), in collaboration with the Clemson University Center for Workforce Development (CUCWD), has developed a comprehensive virtual reality-based learning system. The available e-learning materials include eBooks, mini-video lectures, three-dimensional virtual reality technologies, and online assessments. Select VR-based materials were introduced to students in a sophomore level mechanical engineering laboratory course via fourteen online course modules during a four-semester period. To evaluate the material, a comparison of student performance with and without the material, along with instructor feedback, was completed. Feedback from the instructor and the teaching assistant revealed that the material was effective in improving the laboratory safety and boosted student's confidence in handling engineering tools.

Keywords: virtual reality; online learning materials; engineering education; undergraduate laboratory, teaching methodology

1. Introduction

The undergraduate engineering teaching process needs to actively adapt with changing education trends to better prepare students for a competitive global environment. Mechanical engineering students receive classroom theory and laboratory instruction in addition to a wide array of supplemental knowledge to help prepare them for diverse roles after graduation. An important goal for academic institutions is the full employment of graduates in the workforce with life-long learning skills and aptitude to contribute in a corporate environment. The problem-solving demands in manufacturing facilities typically differ from university scenarios. For instance, when designing a machine component in class, all relevant information is generally provided within the problem description. The student then uses this data to apply a rigorous solution method which is graded based on how efficiently the design works. Whereas in industry, the parameters and/or design method must be either deduced from past practices, taken from industry codes, and/or in some cases assumed from experience, all of which constantly evolve due to current technology, government regulations, and other factors. Further, an important consideration in the component approval process is likely the return on investment. This leads to varying expectations between university and industry which can be reduced by providing students with a more practical and extensive hands-on approach.

Although student performance expectations may vary between faculty and employers, it is the consensus of both groups that fresh graduates lack multiple key skills. These skills were analyzed by Danielson et al. [1] in an effort to categorize weaknesses among new mechanical engineering graduates conducted a survey of nearly 3000 university educators and industry supervisors. The authors listed 15 key skills as weaknesses among the BSME graduates from which three will be discussed in this paper as they arise due to a lack of hands-on experience. Figures 1 shows the percentage of educators and supervisors who feel that a given skill is lacking among the graduates. As illustrated, a higher percentage of industry supervisors feel there is a lack of practical experience and experimental procedure knowledge as compared to university educators. This can be attributed to the specialized nature of industrial jobs, and the fact that industries often update their technology and equipment at a much faster pace than universities in their laboratories. On the other hand, the percentage of both educators and supervisors who feel a lack of an overall system perspective among graduates is simi-

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lar. Overall, this disparity in the opinions between university educators and industry supervisors infers that the standards of expectations are different in these two environments. Regardless of the above perspectives, these three skills are important for a competent mechanical engineer and can be gained through hands-on experience in the laboratories and/or in a controlled virtual environment.

The lack of adequate practical experience among ME graduates can generally be attributed to infrastructural lags, curriculum limitations, and/or safety concerns. The stringent industry standards and codes coupled with funding limitations to upgrade university equipment make it often difficult for schools to stay up-to-date with industry. Moreover, even if the proper equipment is available it is often difficult for an instructor to impart the theoretical concepts while simultaneously demonstrating them in the laboratory during a semester. Finally, proper precautions must be taken while training new students on how to handle sensitive, and occasionally dangerous, equipment in a safe manner. A virtual environment can bypass these limitations by providing the teacher with a representative system that is safer, cheaper, and easier to update when required. Virtual Reality (VR) as defined by Feiner et al. [2] is "A system that attempts to replace much or all the user's experience of the physical world with synthesized 3D material such as graphics and sound" (p. 52). VR based technologies are expected to have a bright future in serving as a supplement in the engineering education field as they offer many advantages over traditional methods. Specifically, this education methodology offers students quick feedback, diverse and challenging practice opportunities, and a self-study-based environment which is expected to be more efficient, facilitate standardization, and support distance learning.

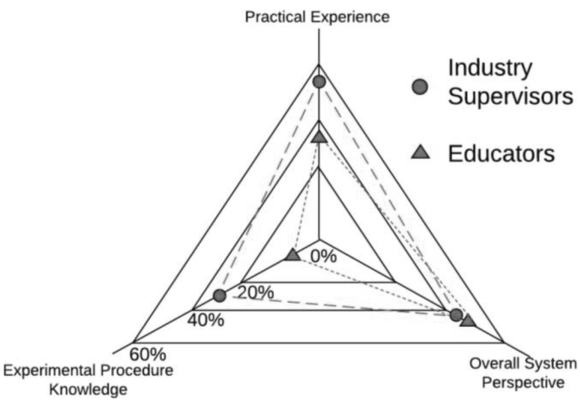

Fig. 1. A Comparison of industry supervisor's and educator's opinions (In percentage) about weaknesses in mechanical engineering curriculum and preparation of its graduates (Adapted from S. Danielson et al., 2011) [1].

The advantages of using virtual reality technology have been proactively demonstrated by various researchers in their respective disciplines. For instance, the efficiency of using multiple dimensions for training purposes was demonstrated by Perdomo et al. [3] when they studied the impact of 3D visualization as a tool for construction education. It was reported that students found it more helpful to visualize structures in three dimensions when compared to studying 2D drawings. The researchers also mentioned that this approach facilitated distance learning without any significant manpower or financial/technological investments. Lee et al. [4] revealed that the use of virtual reality was easier to implement in other non-educational institutions for training as well as research collaboration. In their study, the internet allowed multiple users to utilize a Virtual Reality Modeling Language (VRML) to create a model of the human brain and study various neurological diseases. This approach proved advantageous in remotely educating a diverse group and promoting research and understanding of a complex three-dimensional entity. Similarly, Bell and Fogler [5] developed virtual environments that helped in teaching students about hazardous conditions and accidents that can take place in a chemical plant. This approach eliminated the risk of placing the students in a hazardous or harmful environment.

Shelton and Hedley [6] demonstrated statistically that the use of virtual reality methods can help to improve student performance. These authors used augmented reality to teach students about earth-sun relationships and found that the students understood the concept better with virtual reality. The cost reduction benefits of virtual reality were investigated by Caudell and Mizell [7] by applying augmented reality to manufacturing processes. This approach eliminated the use of templates for manufacturing and increased efficiency in human involved operations such as aircraft maintenance. Angelov and Styczynski [8] developed virtual reality-based teaching material for electrical plants. They concluded that such an approach has the advantage of representing a complex system in a simple manner and keeping the schooling system up-to-date with the latest industry trends. The advantage of virtual reality for self-online learning was demonstrated by Ou et al. [9] who developed an engineering course on hydrology with the help of a virtual learning environment. Similar successes were achieved by Sampaio et al. [10], Kerawalla et al. [11], Sims [12], Piekarski and Thomas [13], and Bajura et al. [14] in the fields of civil engineering education, primary school education, aircraft design, civil construction, and medical imaging. Per Zelaya et al. [15], the younger generation relies heavily on the internet for information seeking and learning. The availability of online materials helps in reaching a wider audience. Bertrand et al. [16] reported that an immersive virtual environment with higher degrees-of-freedom can be beneficial for the training of technicians. Ota et al. [17] state that using VR in surgical education has several benefits, including reducing length of surgical residency program from to 5 to 3 years thus saving approximately $600,000/trainee. The authors attribute this to the ability of VR in assisting trainees to be placed in virtual environments for rarer surgical procedures.

The above discussion provides a compelling reason to study virtual reality's effectiveness as a teaching tool in the mechanical engineering field. This article analyzes the impact of developed VR materials in an undergraduate laboratory course (ME2220) at Clemson University. For the study, sophomore mechanical engineering undergraduate students were invited to use the learning materials created by CA^{2}VES as a supplement to their coursework. The research objective was to analyze the developed material in terms of learning impact on fundamental laboratory skills. The remainder of the paper is organized as follows: Section 2 gives a summary of the materials that were created by CA^{2}VES, Section 3 illustrates the implementation and evaluation procedure of the materials into the course, Section 4 presents the data and its inferred results, and Section 5 provides the feedback obtained from the faculty who teach the course. Finally, Section 6 presents the conclusions of the research.

2. Virtual reality based learning materials in undergraduate laboratory

Clemson University is a land grant institution with students studying in the fields of agriculture, business, engineering, nursing, and science. The Department of Mechanical Engineering graduates an average 175 students per year. With the goal of improving the standard of education for technology and engineering students, the Clemson University Center for Workforce Development (CUCWD) in collaboration with the Center for Aviation and Automotive Technical Education using Virtual E-School (CA^{2}VES) have developed a complete virtual environment based educational system for training. The developed material and delivery platform facilitate distance education; the architecture is shown in Fig. 2. These e-learning resources are composed of e-books, virtual reality interaction modules, training videos, self-assessment modules, 3D visualizations, etc. which cover automotive, aerospace, and manufacturing disciplines. The material was then compiled and released on the website www.educateworkforce.com for distribution in support of industry training programs as well as college courses. A more detailed explanation of the work has been explained by Schkoda et al. [18] and Patel et al. [19]. The various components of the material are as follows:

- *Self or Instructor Led Section*
  These materials provide a brief introduction of the target content that the students are going to learn including the goal, objectives, and expected learning outcomes. It also includes instruction about how to use the Graphical User Interface (GUI).
- *eBooks*
  The eBooks were compiled by experts with rich experience in STEM education fields. They contain many diagrams and illustrated text along with detailed theory about the subject matter. The computer interface also provides the users various navigation tools and research options. To accommodate students with special needs, extra

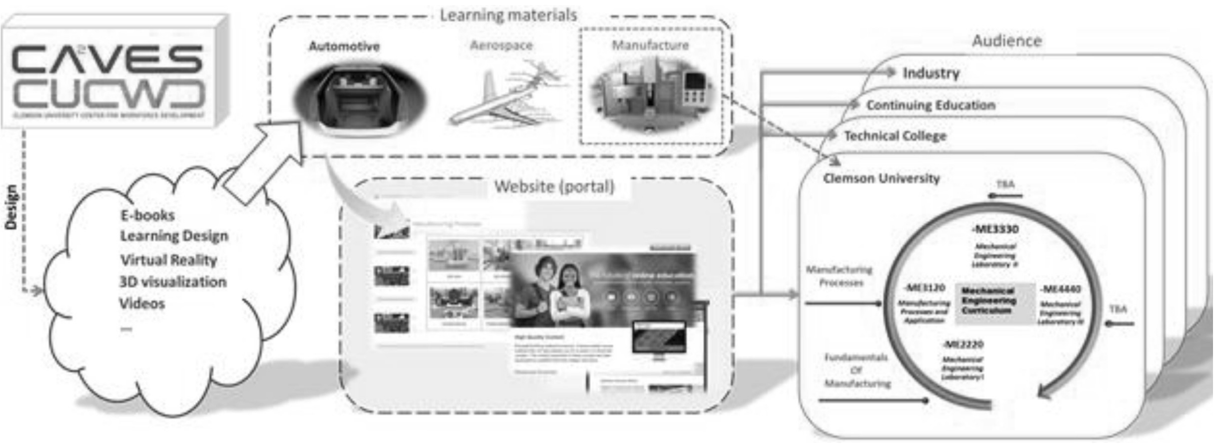

Fig. 2. Overview of automotive and aerospace e-learning materials.

features have been added to the interface (e.g., variable font size, audio subtitles, etc.)

- *Mini-Video Lectures*
  As an additional means to provide students a better understanding of the theory concepts, multiple mini-video lectures were developed based on the eBook content. To make the section more interactive and easily viewable, the lectures offer interactive subtitles so that students can skip to any part of the lecture and/or review a specific topic.
- *Virtual Reality Simulations*
  A project goal is to apply virtual reality concepts for teaching, and this section plays the most crucial role of all. Various virtual reality simulations have been created to provide students with a safe virtual environment to practice the more hazardous technical learning tasks. For example, the safe operational procedure to use power tools including grinders with a magnetic part lock? These simulations were created using 3D CAD tools and virtual reality software packages. Prior to entering the virtual environment, the students are provided with the learning objectives and the specific tasks required to complete the exercise. For instance, Fig.3 shows the virtual environment simulation for using a grinding machine.
- *Activities and Assessments*
  To self-assess their progress, this section provides students with various activities and assessment tools. Exercises have been added at the end of each module for participants to practice what they learn in the module before moving to the next section. In this manner, they receive immediate performance feedback and can choose to review the content again if necessary.

3. Integration into undergraduate mechanical engineering course at Clemson University

The effective validation of a new learning paradigm typically requires a case study to assess and improve the product. To validate the CA^{2}VES developed e-learning materials, sophomore mechanical engineering students were invited to voluntarily use this online content as a supplement for their laboratory course with an incentive for extra credit. The successful completion of each module added a 0.02 bonus point to the student's course score with a total possible addition of 0.28 to a maximum score of 4.0. The successful completion of a module required the student to watch a short instructional video and then complete the assessment activities with a score of 80% or above. The available modules for this course have been listed in Table 1.

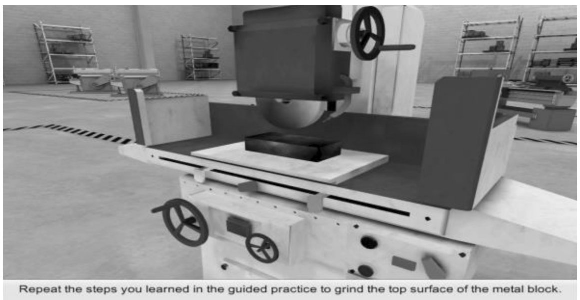

Fig. 3. Virtual reality simulation demonstrating a grinding machine.

4. Assessment of e-learning materials

The parameters chosen for assessing the learning impact of the e-learning materials were the student's course grade and overall university GPA. The university GPA was taken as a normalizing factor whereas the subject grades presented the student's performance in the course. The usage of the material was quantified based on the number of learning modules completed. The course grades and the overall GPA used a 4-point scale, with A being 4 and D being 1. A total of six semesters were taken into consideration with the initial two semesters being ones in which no VR material was used. This was to establish a baseline for comparison purposes.

Table *2* shows the distribution of the grades and GPA along with the average number of modules completed by each grade category. An initial drop was observed in the number of students receiving A and B which can be attributed to the fact that the previous course structure was based on theory explanations rather than practical demonstrations. This was confirmed through an interview of the instructor who stated that the course was redesigned in successive semesters to better accommodate the learning modules. The performance of the students

Table 1. Mechanical engineering laboratory supplemental e-learning modules

Module	Title
1	Popular Measuring Instruments
2	Industrial Instruments: Temperature & Pressure
3	Industrial Instruments: Force, Torque, & Flow
4	Electrical Measuring Instruments
5	Properties of Engineering Materials
6	Engineering Materials
7	Production Process
8	Machining Operations
9	Special Processing
10	Safety at Facilities
11	Environmental Control and Noise
12	Material Handling and Electrical Safety
13	Machinery, Hand Tool and Equipment Safety
14	Personal Protection and First Aid

Table 2. Distribution of student grades prior to virtual reality supplemental materials

Semester (Total Enrollment)	Student Class Grade	Number of Students	Average Number of Modules Completed	Average Student GPA
Fall 2013 (129)	A	34	N/A	3.6
	B	73		3.1
	C	19		3
	D	3		1.7
Spring 2014 (150)	A	37	N/A	3.5
	B	93		3.1
	C	21		2.7
	D	0		0
Fall 2014 (126)	A	23	4.9	3.6
	B	71	1.5	3.1
	C	30	1.2	2.8
	D	2	5.5	2.4
Spring 2015 (149)	A	33	4.4	3.6
	B	94	1.3	3.10
	C	18	0.7	2.8
	D	4	0.3	2.7
Fall 2015 (149)	A	63	4.5	3.4
	B	81	2.8	2.9
	C	5	1.8	2.5
	D	0	0	0
Spring 2016 (160)	A	63	4.9	3.3
	B	84	2.5	2.9
	C	12	1.7	2.5
	D	1	1	1.9
Fall 2016 (117)	A	43	2.4	3.4
	B	66	2	2.9
	C	8	1.9	2.6
	D	0	0	0
Spring 2017 (144)	A	59	2.5	3.4
	B	82	1.55	3
	C	3	2.3	2.6
	D	0	0	0
Fall 2017 (135)	A	66	4.6	3.4
	B	66	2.9	3
	C	3	1.6	2.6
	D	0	0	0

in the course was analyzed for each of the grade categories from A through C whereas the students who failed the class with a D were not considered as part of the analysis since they constituted a very small percentage of the class. Fig.4 through Fig.6 display the study findings which are summarized in Table 2.

To evaluate student performance trends, each grade category has been analyzed individually over six semesters. Figure 4 shows that the number of students receiving A and B letter grades increased significantly after the VR modules were implemented. For instance, the number of students with an A grade increased from 26.4% (Fall 2013) to 48.9% (Fall 2017). On the other hand, the number of students with a C grade decreased. When this data is analyzed along with the data from Fig.5, it can be observed that the grades improved despite a slight decrease in the average university GPA. This leads to the conclusion that the students who performed lower at the university level achieved better grades in this course. This pattern also correlates with the finding by Shelton and Hedley [6] that show that virtual reality-based learning helps students with lower grades understand better. Moreover, a spike in the grades was observed when four of the modules were mandatory assignments during the Fall 2015. Lastly, students with better grades generally completed more modules and showed a remarkably higher performance improvement as per Fig.6. In other words, the increase in students with grade A is much higher than other grade categories. But once four of the modules were made mandatory there was a sharp increase in the average number of students who completed those modules in the lower grade groups. This shows the inherent lack of drive of the lower percentile students to put in extra effort towards their courses without incentive.

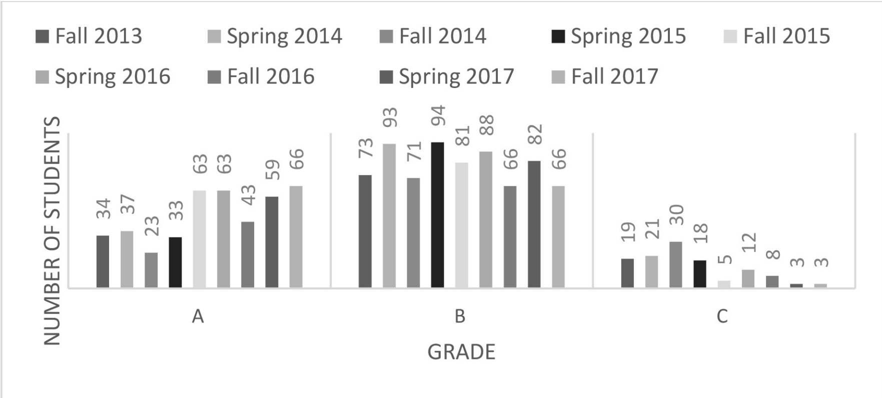

Fig. 4. Distribution trend of course letter grades before (Fall 2013 and Spring 2014) and after (Fall 2014 through Fall 2017) introduction of virtual reality supplemental material.

Figure 7 gives a better representation of the modules completed by each individual student with respect to their grade. The right-hand Y-axis shows the total completed modules (stem plot), left-hand Y-axis the grade (line plot) and the X-axis represents individual students. The data has been sorted in the descending order of overall university GPA in each grade category. As observed, students with better grades and GPA generally completed more modules although there were some exceptions at random. However, most of these exceptions were concentrated around the points where grades changed from B to A and C to B due to the extra effort by the student to boost their grade. It is also seen that a

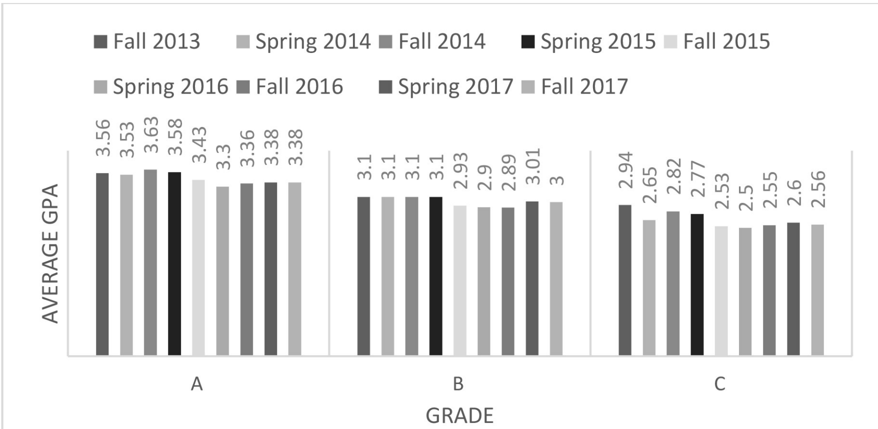

Fig. 5. Distribution trend of average student GPA in each grade category.

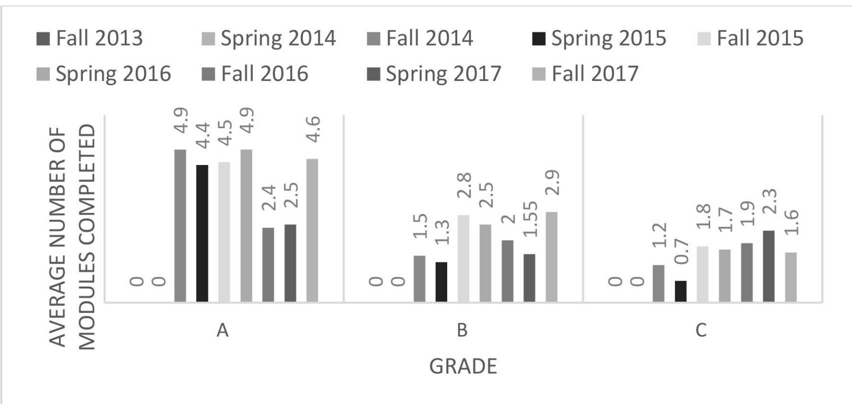

Fig. 6. Distribution trend of virtual reality modules completed in each grade category.

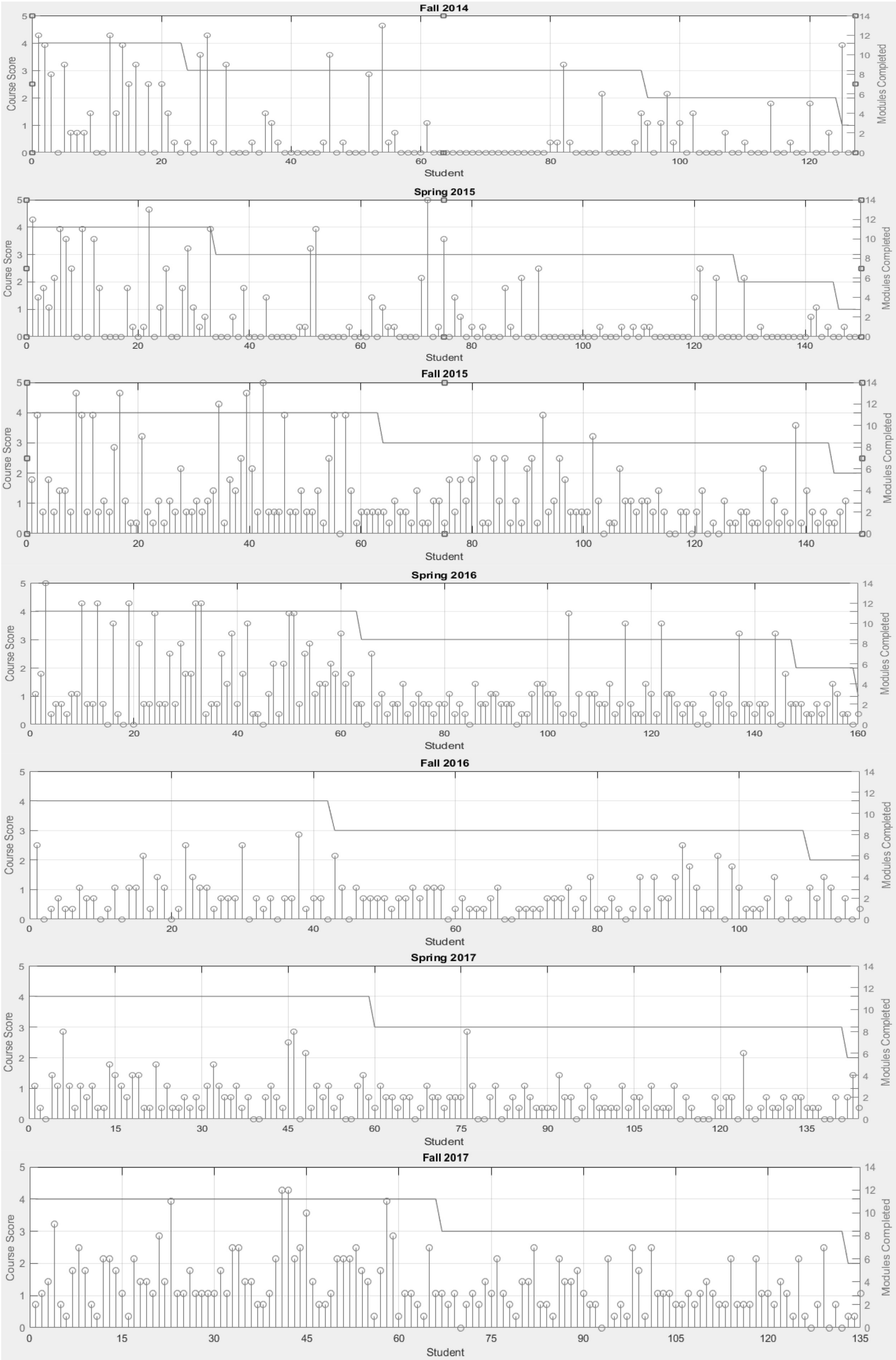

Fig. 7. ME 2220 course scores versus completed modules.

few students chose not to use the material at all despite the modules being made into a compulsory assignment from fall 2015.

5. Student feedback survey

To complete any pilot study, it is essential to obtain feedback from the participants. For this purpose, a brief post module survey was handed to the students at the end of each module. Student participation was voluntary with no added incentive for response. A total of 9 questions on a Likert response scale were used to assess the modules. In addition to this, two subjective questions were added. The survey form is presented in the Appendix of the paper. The Likert responses were scaled 1 through 5, with 1 being 'no gain' and 5 being 'great gain'. The Likert responses for each module was analyzed. The results are as shown in Fig.8 using a box and whisker plot. The median of each module gives the overall performance as per the students' views. To be considered a success, a median value of at least 3 is needed. Accordingly, modules 10 and 11 had the lowest rating. Looking at the individual subjective responses, it was found that students found some minor problems with how the questions were phrased and few minor data errors.

Table 3 presents the number of responses for each module. It can be observed that modules 3 through 6 (mandatory modules) had relatively more responses. Some of the other subjective responses mentioned the videos to be shorter to cut down time taken per module.

6. Feedback of the course instructor and laboratory teaching assistants

To further evaluate the e-learning materials, the course instructor and teaching assistants for the course provided their observations. The instructor indicated that the created modules provided better coverage of the industrial safety content. The instructor also stated that one of the challenges in delivering laboratory classes is promoting consistency across multiple sections. The e-learning modules addressed this challenge by providing uniform delivery of the material to all students regardless of the faculty assigned to cover that section. Also, the comprehensiveness of the content along with assessment and automatic scoring at the end of each module reduced the burden required to integrate the modules into the course. One of the advantages of the modules that the instructor felt was most important addressed the ability to prepare students for the hands-on industrial safety activities. The students were required to complete the industrial safety modules prior to the start of laboratory, so they arrived to class with the vocabulary and fundamental concepts required to promote deeper learning and exploration. This knowledge was especially important considering the near miss safety incident that occurred in the laboratory prior to emphasizing

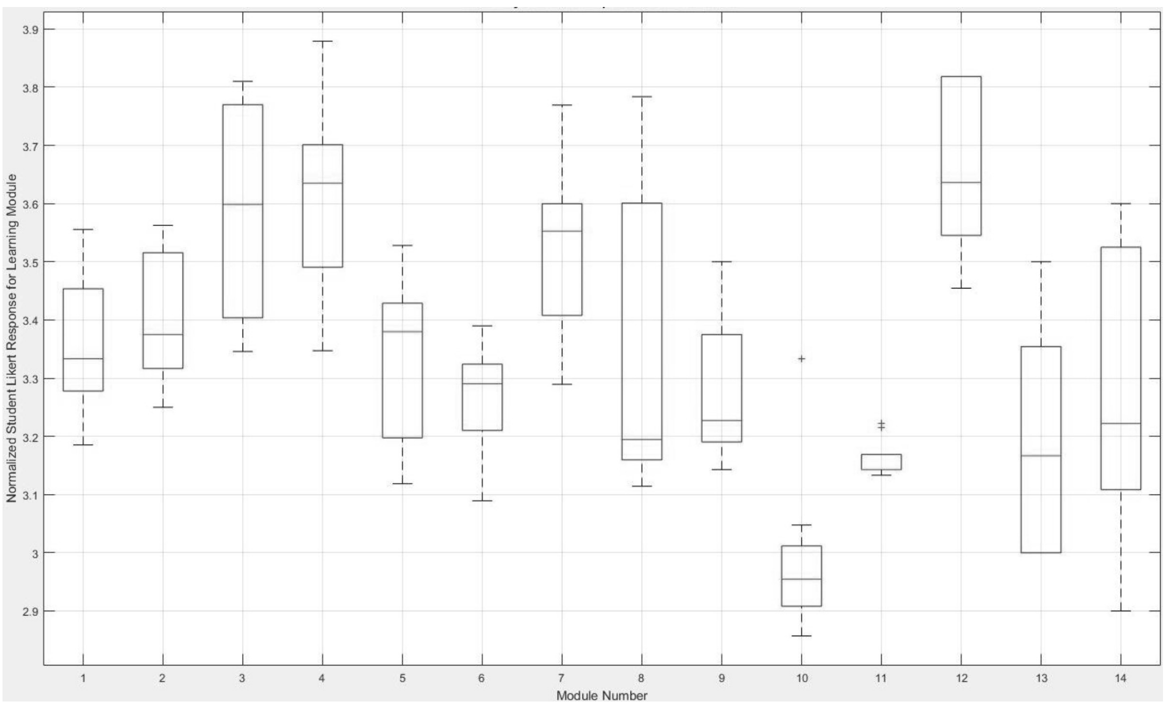

Fig. 8. Summary of Likert Responses for individual modules.

Table 3. Number of Responses for individual modules

Module	Number of Responses	No Responses	Average Module Scores	Module	Number of Responses	No Responses	Average Module Scores
1	27	17	92.4	8	44	9	93.5
2	16	6	88.6	9	29	11	86.1
3	141	47	89.7	10	26	12	83.2
4	137	46	88.7	11	17	7	91.1
5	135	40	76.3	12	14	4	94.5
6	130	32	78.8	13	15	7	84.9
7	42	12	91.7	14	12	4	91.9

the industrial safety content. The modules that were optional were used to reinforce, or supplement, concepts learned in laboratory.

The laboratory teaching assistants reported that the use of the modules beforehand helped in boosting the confidence level of the students when handling the equipment for the first time. The online material covered most of the basic safety procedures that were to be followed in the laboratory which reduced the risk for any accidents. In addition, the VR modules also helped the students in preparing for the final assessment. However, the teaching assistants mentioned that using a different website for uploading grades was a hindrance and requested greater back end support for easier integration. They stated that a more easily accessible website would help the instructors better embrace the material. The comments by the instructor and the teaching assistants were found to be similar regarding the safety advantages in using the VR based teaching supplements.

7. Conclusion

Virtual Reality is an emerging technology with unlimited potential in the engineering education field. This paper analyzed student learning performance in an undergraduate mechanical engineering course at Clemson University to gain insight into the effectiveness of virtual reality as a teaching supplement. The analysis showed that VR based material helped students to better grasp the subject matter and allowed the instructor to design the course without costly laboratory upgrades. However, from the initial drop in grades it was concluded that some effort is required to integrate the material in the conventional teaching environment. However, the time needed to integrate the two is quite short, about two semesters, and hence it is quite easy to shift to the more robust VR based teaching methods. The faculty feedback shows that the integration process requires some outside assistance as it involves using new technologies which the instructor may or may not be familiar with. This assistance was provided by CA^2VES in the form of back end support (grade uploads, website maintenance and troubleshooting). Once the framework was setup, it was easy for the instructor to focus his efforts in engaging the class in more creative and interactive experiments. This approach can be used overall for any technical college, university or industry. Once the initial setup and troubleshooting is completed, the VR material integrates well with any educational system. For a more global impact, the material may be disseminated via the internet in the form of software packages. In conclusion, it can be said that virtual reality is a great asset in the field of engineering education and research. Its use is expected to benefit engineering students and enhance their knowledge base and make them more readily hirable by industries.

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Appendix

Module Title: ____________________________ Date: __________________
Score Received: ____________________________

As a result of your work on this module, what GAINS did you make in your UNDERSTANDING, ATTITUDES, and SYNTHESIS of each of the following? Please select the most appropriate response by checking the box.

Your understanding of class content through the VR module.

	No gain	**Little gain**	**Moderate gain**	**Good gain**	**Great gain**	**Not applicable**
1. Safety precautions while handling setup/equipment.	○	○	○	○	○	○
2. Principle behind the operation of setup/equipment.	○	○	○	○	○	○
3. Material properties subjected to the given process.	○	○	○	○	○	○

Module impact on your attitudes.

4. Confidence in handling equipment independently.	○	○	○	○	○	○
5. Interest in handling setup/equipment.	○	○	○	○	○	○
6. Ability to visualize in 3 dimensions.						
7. Developing a sense of presence in the virtual environment.	○	○	○	○	○	○

Integrating your learning.

8. Applying what I learned in this class to other situations.	○	○	○	○	○	○
9. Ability to decide which process is best suited for the design requirements.	○	○	○	○	○	○

Please share your thoughts with written comments regarding the two questions.

10. What would you recommend improving in the module	○	○	○	○	○	○
11. Would you recommend this online module to a friend—yes/no? Why?	○	○	○	○	○	○

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Rebecca Hartley, PhD, is the Director of Operations at the Clemson University Center for Workforce Development (CUCWD) and the NSF ATE Center for Aviation and Automotive Technological Education using Virtual E-Schools (CA^2VES) and has spent the past nineteen years working in higher education administration in the areas of undergraduate admissions, graduate admissions, academic records, and student affairs. She is also Chief Workforce Development Officer with the Advanced Robotics in Manufacturing (ARM) Institute. She earned a Bachelor of Science from Western Carolina University, a Master of Public Administration and a PhD in Public Administration and Public Policy also from Auburn University. Prior to joining the Clemson University Center for Workforce Development and CA^2VES, she served as Director of Graduate Admissions & Records at the University of Montevallo in Alabama.

Zachary Trabookis joined the Clemson University Center for Workforce Development (CUCWD) department in 2013 as Web Services Program Manager focusing on E-learning initiatives with technological training for the Massive Open Online Course (MOOC) platform EducateWorkforce. Zachary holds a BS in Computer Science and MFA in Digital Production Arts from Clemson University. Prior to joining CUCWD, Zachary worked 7 years in the private sector developing web and standalone applications that consist of financial reporting, database syncing, training simulations, and loan origination.

Zaker Syed is a PhD candidate at Clemson University, having completed his MS in mechanical engineering from Colorado State University. His research focuses include nonlinear control systems, thermal systems, and development of education methods using virtual reality. His current research is focused on nonlinear control system strategies for automotive engine cooling. He is a member of the CA^2VES research team at Clemson University aiming to develop educational material for engineering education using virtual reality.