AC 2011-2246: DIGITAL ADDITIVE MANUFACTURING FOR ENGINEERING EDUCATION: A VIRTUAL RAPID PROTOTYPING SIMULATOR APPROACH

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Digital Additive Manufacturing for Engineering Education: A Virtual Rapid Prototyping Simulator Approach

Abstract

The objective of this paper is to introduce, implement, and further enhance engineering education in digital additive manufacturing using a virtual Rapid Prototyping (RP) simulator within the established programs of Industrial, Manufacturing and Systems Engineering and Mechanical Engineering at the University of XXXX (XXXX). This paper describes a state-of-the-art virtual rapid prototyping simulator in 3D environment using XNA framework. The purposes of the virtual RP simulator are allowing the users to get familiar with the basic commands and functions of the real Fused Deposition Modeling (FDM) 3000 facility and learning how to operate the FDM 3000 machine. The paper also aims at developing an effective learning model to facilitate student's learning in digital additive manufacturing. The students are separated to the control group and the experimental group to validate the use of the virtual Rapid Prototyping (RP) simulator. Student learning from both real and virtual environment are evaluated and discussed in this paper.

Introduction

The objective of this paper is to introduce, implement, and further enhance engineering education in digital additive manufacturing using a virtual Rapid Prototyping (RP)**.** The purposes of the virtual RP simulator are allowing the users to get familiar with the basic commands and functions of the real Fused Deposition Modeling (FDM) 3000 facility and learning how to operate the FDM 3000 machine. Currently, globalization has changed the landscape of manufacturing industry. More and more manufacturing companies in US are moving out to oversea due to inexpensive labor cost and other resources. Manufacturing industry becomes sensitive about cost effectiveness issues due to recent economic crisis. Manufacturing companies are cautious about sustainable workforce, particularly in equipment operation. The workers' faulty operations could cause significant damage of the facilities and personal injuries and safety hazards. Moreover, through recent literature survey, the fundamental challenging problem in manufacturing education: (1) How to improve teaching and learning effectiveness in online course and facility training; (2) How to better educate students online facility training without interaction with instructors[1]. Therefore, the intensive, informative and 24 hour access training tools are demanded.

Additive Manufacturing (AM) technologies are becoming popular due to their rapid development and improvement in capability. Several technologies collectively known as RM have been developed to shorten the design and production cycle, and have transformed many conventional manufacturing procedures. According to Society of Manufacturing Engineers (SME), AM is a broad term including the use of rapid prototyping, rapid tooling, and the direct use of layer manufacturing technologies to produce final products quickly [2]. Before the production starts, a prototype called

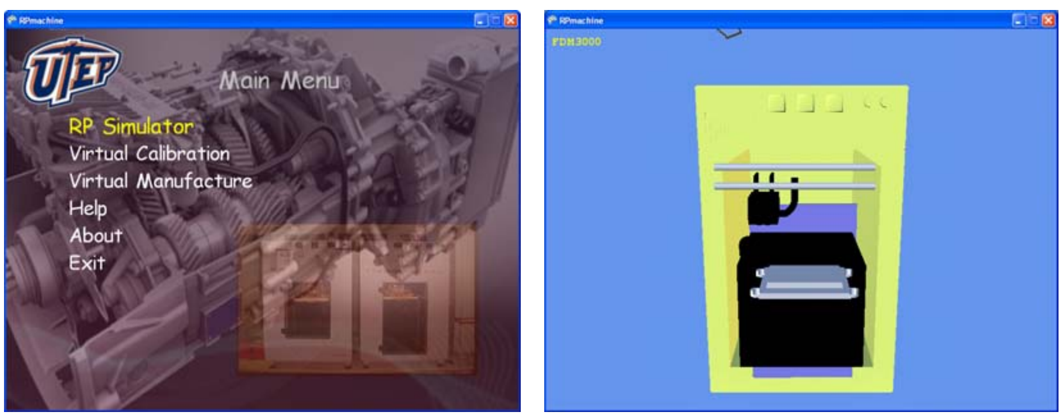
Functional Prototype is used as part of design cycle to complete testing of the product. Numerous commercial AM systems for various materials and sizes are now available on the market. Rapid Prototyping (RP) is one of AM techniques. The fast creation of a prototype is known as RP [3]. Layered manufacturing is actually better known as RP where the fabrication of part by depositing or bonding successive layers. The technologies now available include a variety of different processes, such as Stereo Lithography, Selective Laser Sintering, Fused Deposition Modeling, 3D Printing, Shape Deposition Manufacturing and Laminated Object Manufacturing. The application of RP methods to the fabrication of customized molds, dies, and tools used to produce parts is called Rapid Tooling [4,5].

Applications of AM can be found in different sectors. For instance, researchers at the University of Texas at Austin have reproduced human bone shapes using SLS to form titanium castings during the late 2000s [6]. Casting dies for automobile deck parts were fabricated by LOM [7]. IBM used SL to produce operating display units of its ThinkPad tablet computer. A turbine part with a complex shape was built by 3D printing using a Pro Metal RTS-300 machine [8]. In general, AM allows three dimensional geometry parts to be fabricated by which the designers can shape parts optimally without any constraints imposed due to forming, machining, or joining. Moreover, it utilizes the computer description of the part shape directly, and allows integration of the Computer Aided Design (CAD) with the Computer Aided Manufacture (CAM) of the part [9-11]. Consequently, the manufacturing cycle with seamless transition through design, simulation, modeling and fabrication is performed.

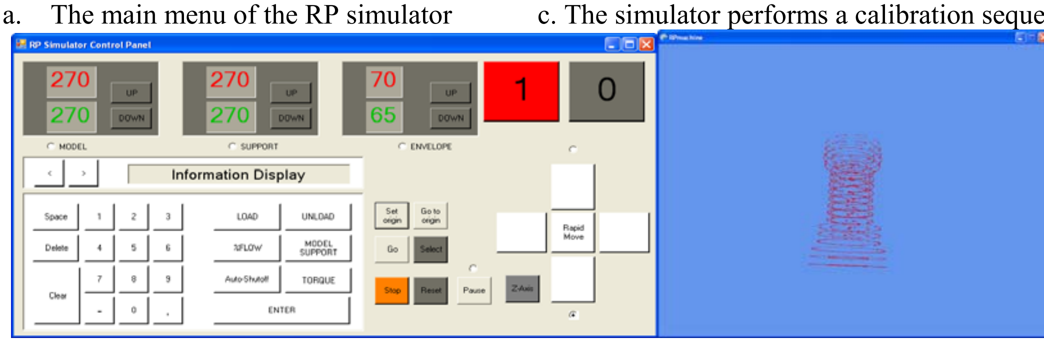
The term of "Virtual Facility" (VF) is referring to a facility which is normally in a digital format and able to mimic the real faculty. The main purpose of the use of VF is to allow the user to acquire training, improve operation skills and be familiar with the real facility before actually implementing it. In general, the VFs are fabricated and characterized in the computer systems which make them more safe and cost-effective. The VF is normally developed through programming languages. The characteristics of the VF include but not limited to error free data, innovating testing and evaluating features of a design which in user's perspective can help create ideas [12-14]. Hence, it can optimize the prototyping process, improve part quality, enhance fabrication efficiency, and lower the model making cost significantly.

Development of Virtual Facility – The Rapid Prototyping Simulator

In recent years, the authors have developed a Virtual Facility (VF) called the Rapid Prototyping (RP) simulator (see Figure 1-a) to mimic the real Rapid Prototyping (RP) machine, FDM 3000 made by Stratasys Inc. through a few funding supports. Basically, the purpose of the RP simulator development is to provide basic functions and offer students 24 hours access of the virtual machine which is very similar to the **real** FDM 3000 machine. Therefore, students are able to learn more effectively before they operate the real facility. Microsoft 3D Studio Max and XNA framework have been used to model the real FDM 3000 Rapid Prototype machine and simulate the functions of the machine in the 3D environment. There are three different modules included in this self developed software: (1) Control Panel, (2) Virtual calibration and (3) Virtual manufacturing. In (1), users are allowed to control basic functions, rotate, zoom in/out, turn on/off and manipulate the RP simulator. The goal of this module is to support the users to get familiar with the basic commands and functions of the real FDM3000. When the user move his/her mouse to a certain button on the 3D virtual machine, the description/introduction of the button function will pop up and instruct the user how to operate that part on the real machine **(**see Figure 1-b**).** In (2) the user can practice calibration of the machine in its virtual calibration environment. It is critical to calibrate the FDM machine frequently. Improper calibration can result in misalignment or displacement of its support material from its proper XYZ-axis position. Because there are several functional keys and buttons in the front panel of the machine, therefore, it is very easy to get confused by the user. Moreover, the user may run the machine before the material is up to the required temperature. Consequently, it will destroy the tips of the FDM machine. In general, virtual calibrations can help students familiar with the calibration process and make sure the machine is in good condition **(**see Figure 1-c**).** In (3), the simulator is allowed to upload a .stl files, build up slices layer by layer along the z-axis (see Figure 1-d). The simulator will analyze the input file and display the slices that make up the model. Here, the user is allowed to specify how many slices he or she wishes to have through setting the height of the slice**.** Furthermore, the users can access the user manual through selecting the Help option on the main menu.



a. The main menu of the RP simulator c. The simulator performs a calibration sequence



b. The control panel of the virtual RP machine d. Slices the model into layers

Figure 1 a-d: The Rapid Prototyping (RP) simulator developed by University of XXXX

To date, there is no comprehensive education model fully integrating available Internet technologies and virtual reality into classroom with an emphasis on the improvement of students' skills in problem solving and information seeking [15]. Therefore, the authors propose to use a digital simulator based approach to explore the use of Internet for active learning and problem solving skills enhancement in engineering curriculum. Basically, the RP simulator will serve as a critical virtual facility to achieve the following learning objectives for students: 1) Enhance students for more advanced study of Internet based rapid manufacturing systems; 2) Accelerate the problem solving skills transfer from classroom to practice in real world.

Problem Description

The ABET Engineering Criteria states the engineering students should be able to communicate effectively, function on multi-disciplinary teams and use the techniques, skills and modern engineering tools necessary for engineering practice. This requires the development of creative education model to promote team-based collaborative learning focused on engineering projects, establish close ties among different schools and programs, and promote interdisciplinary education. Yet current education models are primarily based on the learning in the classroom with a clear delineation between disciplines. Students attend the lectures and are evaluated through homework problems, class projects and exams. Even though the importance of team work has been stressed over the years for the successful engineering career development, the extent of implementation is limited to the team projects in the classroom. Many engineering/business courses are pure lecture-based, and do not usually contain components that help student to boost their communication skills within the framework of engineering problems. The limited exposure to this critical success skill has resulted in isolated learning experience. Students lack the broad understanding in other areas of study and oftentimes speaking different languages between the disciplines. Many industries (i.e., automotive, aerospace, electronics, etc.) are complaining about the lack of preparation future engineers are receiving in colleges and universities. The industries pointed out that there exists a huge, yet common deficiency among the engineering students, asking that students should learn how to communicate effectively [16]. This is aligned with the exponential growth of advanced, sophisticated technologies that resulted in an increasing demand for engineers [17, 18]. The report prepared by the Society of Manufacturing Engineers (SME) listed 14 competency gaps that engineering graduates are lacking quality, product/process design [19]. To address this concern, there is a need to develop and incorporate an innovative education model to engineering curriculum to ensure that engineering graduates are equipped with appropriate knowledge and necessary skills in active learning, communication and information seeking.

What is giving added challenges to such education model is the emerging distributed operations in industries. In recent years, the centralized companies of the past have been replaced by geographically dispersed, remotely located companies collaborating on a common project. The technical advances, especially the Internet, have been the major driving force behind this trend. Surprisingly, the full potential of these technologies are not currently used in the classroom settings [20, 21]. There is no comprehensive education model fully integrating available Internet technologies into classroom with an emphasis on the improvement of students' skills in information seeking and communication [22]. In most cases, it is limited to the on-line course delivery, emails and e-bulletin board between students and instructors [23]. Therefore, the authors have implemented **a digital simulator based approach** to explore the use of Internet for active learning and information seeking skills enhancement in engineering curriculum.

Digital Simulator Based Approach for Effective Learning

The term "Internet Based Manufacturing (IBM)" refers to the information technology based principle, modeling approaches and computing networks, used to design products with built-in intelligence. According to the Report of the NSF subcommittee on Manufacturing Infrastructure [24], to enable the Nation's Manufacturing Capability, "next generation manufacturing equipment will require the integration of fast manufacturing architecture, intelligent controllers, intelligent sensors and actuators, and innovative machining and tooling concepts". Internet based manufacturing through information and communication technologies are key elements to deploy real-time control of production processes in a global manufacturing enterprise. The role of communication vehicles such as Internet/Intranet in the creation of supply chain management has been recognized [25, 26].

The proposed digital simulator based approach aims at taking advantages of the pedagogical strategies and techniques, to improve students' learning. Basically, asynchronous digital simulator based approach is self-paced, highly interactive, results in increased retention rates, and has reduced costs associated with student travel to an instructor-led workshop. In addition, the digital simulator based approach allows for easy access to the content and requires no distribution of physical materials. This feature translates into the following specific benefits like (1) *Access is available anytime, anywhere, around the globe*; (2) *Per-student equipment costs are affordable*; and (3) *Content is easily update*d.

Despite these potential benefits, empirical studies typically have failed to find statistically significant differences between digital simulator based and face-to-face (FTF) course performance. The major drawback, when compared to synchronous FTF instruction, is the lack of human contact, which greatly impacts learning. While students can use their Web connection to e-mail their instructors or post comments on message boards, FTF classroom real-time interaction between instructor and students may be still superior.

Case Study: Comparison of the Conventional Approach and the Digital Simulator Based Approach for Effective Learning in Additive Manufacturing

XXXX has offered a Additive Manufacturing related course in Spring, 2010. The course title is Rapid Manufacturing Systems (MFG 4395/5390). Basically, the course is an introduction to Additive Manufacturing (AM). AM technologies fabricate three-dimensional (3D) parts using layer-based manufacturing processes directly from Computer-Aided-Design (CAD) models. Direct Digital Manufacturing (DDM) or Rapid Manufacturing (RM) is the use of AM technologies in direct manufacturing of end-use parts. In this course, the students learned about a variety of AM technologies, their advantages and disadvantages for producing both prototypes and functional parts. The faculty is interested in exploring if **a non-traditional teaching approach through the RP simulator** can compete and/or substitute the traditional method (i.e., a face-to-face class). To perform these tasks, we divided the students into two groups.

The first group (8 students) had the course contents (i.e., how to calibrate FDM 3000 machine) presented in the traditional way (i.e., face-to-face) with the instructor. The instructor prepared his own PowerPoint slides and explained operations of the RP machine with the **real** FDM 3000 facilities to deliver instruction. The first group called the "control group" because the students were learning by having face-to-face communication with the instructor. Figure 2 illustrates students learning course materials from the instructor by sitting in the class.

Figure 2: Students in the ME 4395/ME 5390/MFG 5390 - Rapid Manufacturing Systems class located in the A-323 classroom at XXXX

The second group was the "experimental group" because they only used the **RP simulator** instead of running the real FDM 3000 machines to learn "how to operate the RP facilities." This included learning basic components of the RP machine, calibration and viewing a fabrication process of the part through face-to-face communication with the instructor. Figure 3 shows students learning using the RP simulator with the instructor's explanation.

Figure 3: Students learning interactively from the RP simulator in the E-225 Lab at XXXX

All students from both groups were asked to *(1) conduct an experiment to calibrate the model and support tips on the FDM 3000 machine* and (2) *take a written test related to the lectures*. In conducting an experiment on the FDM 3000 machine, all of the students included in the control and experimental groups were divided into teams of 4 (i.e., 4 students in one group). Each individual group was given an identical task of performing the previously determined experiment to calibrate the tips. The part produced in this process can be seen in Figure 4. Therefore, the instructor was able to judge and compare the performances based on how many trials had been taken to get the correct calibration. Moreover, to learn more about the effect of implementing the RP simulator, we also asked the control group to take the RP simulator instruction. Consequently, the difference of learning effect **between** the control group and the experimental group and learning effect difference **within** the control group (since the group learned both approaches) could be captured. Figure 5 shows students in the control and experimental groups discussing “the experiment” and “how to calibrate the FDM machine.” Note that one of the instructors, Mr. Medina also played a role as a facilitator to provide limited instructions in order to avoid damaging the facility during the experiment for both groups.

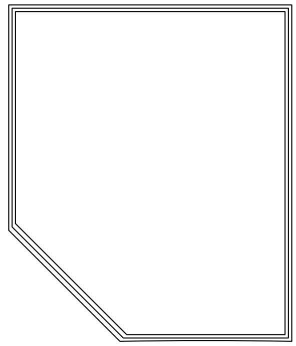


Figure 4: The part produced and used in the process of calibration. The extreme lines show the width of model material laid by the model tip and the central line is laid by the support tip (of support material).

Figure 5: Students in the control and experimental groups participating interactively in calibrating the FDM machine

In the next section, the written test performance from each group will be analyzed and discussed.

Written Test Performance by Both Groups
To analyze and compare the performance of the two groups, a test was conducted after the class but during the course. The test consisted of ten questions in total related to course materials, particularly to the RP operation.

The test scores from both groups were tabulated and shown below (see Table 1):

Table 1: Test results for students in group 1 and 2

Group 1 (Control)			**Group 2 (Experimental)**	
S. No	For 10		S. No	For 10
1	7		1	5
2	7		2	8
3	9		3	3
4	9		4	8
5	9		5	7
6	7		6	8
7	7		7	9
8	7		8	
Average	**7.75**		Average	**7.5**

Note: S. No. 3 in the experimental group is an outliner.

The instruction was given to the experimental group using RP Simulator with a seven-students group. Also, simultaneously instruction was given to the control group consisting of 8 students trained by Francisco Medina, FDM instructor for this course. At the end of the instruction, written test was taken based on their knowledge regarding the concepts of FDM 3000 machine and test comprised of 10 multiple choice questions. The following analysis shows the results obtained from their test showing that there is not much difference in test results between those receiving instruction via the RP Simulator or a live instructor. Here we assume the null hypothesis that the difference between the means of two samples in not significant. So, the alternative hypothesis will be that the difference in means between two samples is significant. We, assume the $\alpha = 0.05$.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S_{X_1X_2} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}}$$

where

$$S_{X_1X_2} = \sqrt{\frac{(n_1 - 1)S_{X_1}^2 + (n_2 - 1)S_{X_2}^2}{n_1 + n_2 - 2}}.$$

After calculating the two sample T test statistic and P-Value = 0.237. Since P – Value is greater than α, we can say that we cannot reject the null hypothesis, that difference is not significant. So, this means that the samples obtained from the Experimental group when compared with the Control group are correlated with each other. So, based on the test we can conclude there is not much difference in performance for the two groups despite receiving different instructional treatments. Note that comparison of results obtained from written test taken after instruction is illustrated in Figure 6.

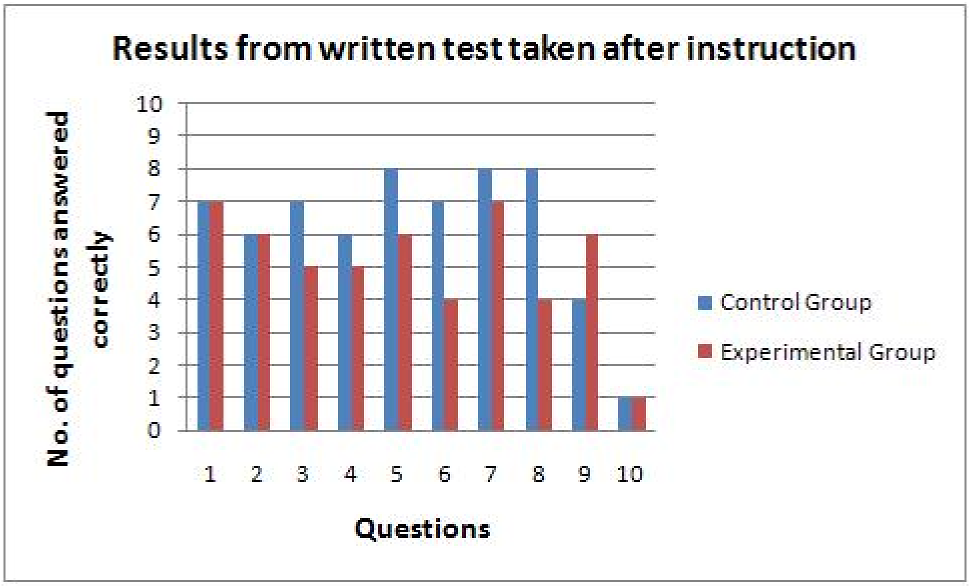


Figure 6: Comparison of results obtained from written test taken after instruction

Calibration Test Performance by Both Groups

As part of the experiment, students were divided into groups and asked to perform calibration of the machine in X and Y axes. The machines used were initially calibrated and given an offset of 0.02 from the calibrated values for the students to perform the calibration of the machines. The calibration values and offset values were recorded. The standard offset of 0.02 was to compare the control and experimental groups. Each group was given a fixed time of 30 minutes to calibrate the machine. The number of trials made and the final values after the last trial or at the end of 30 minutes were recorded. The data collected was analyzed for comparison of the performances of control and experimental groups. All the groups were evaluated for 10 points of which 1 point was for the number of trials made and the rest of 9 points depending on the closeness of the final values to the calibration values. Of the 9 points, 5 were given for giving the increments in right direction as it is critical and basic for the students to know the information for calibrating the machine. As the calibration is an approximation procedure, students were given full 4 points if they could approach the calibration values by 75%, 3 points if they could approach by 60%, 2 points if they could approach by 50% and 1 point if they could approach by 25%. With regard to number of trials made, students were given full 1 point if they could calibrate in 2 trials and 0.5 points if they could do it in 4 trials. Less importance was given to the number of trials as the calibration is a random procedure where lot of experience is required to determine the exact values to be input into the machine to have it calibrated correctly.

Both the control and experimental groups were divided into two groups each for the current experiment. Table 2 shows the initial values in the machines, data collected after the students' completion of the calibration procedure, the extent students approached, points scored by each of the groups and the evaluation procedure. The average points scored by the control groups were 9.75 and by the experimental groups were 7.5. From the data collected, we can see that the students from both the groups approached in the right direction which means that the students could analyze the part produced and input the values accordingly. The difference in the extent of approach and the number of trials may be attributed to the fact that the control group was trained on the machine itself which gave them more insight into the range of values to be input into the machine to achieve calibration compared to the experimental group trained on the simulation software. From the analysis, it can be concluded that **the students trained on the simulation software learnt the process comparative to those trained on the machine but took more trials and could not approach by the same extent due to the lack of previous experience with the machine.** However, it should be noted that the students could learn the process and operate the real machine from their training with simulator. Given more time, they might have completed the calibration process successfully which was the primary motive of the project. Note that one critical thing observed was that students from both the groups took help from the instructor which shows that during the lab experiments, there is a need for the presence of an instructor to speak to them.

Table 2: Analysis of the calibration parts produced

Initial setting							
For B & D	Calibrated	Offset	Difference	For A & C	Calibrated	Offset	Difference
X	-1.106	-1.086	0.02	X	-1.142	-1.122	0.02
Y	0.036	0.056	0.02	Y	0.036	0.056	0.02
Data Collected							
	Control Group				Experiment Group		
	Group A	Group B			Group C	Group D	
Trials	2	3		Trials	4	4	
X	-1.137	-1.101		X	-1.126	-1.098	
Y	0.041	0.041		Y	0.051	0.044	
Approach Extent							
	Difference from offset				Difference from offset		
X	0.015	0.015		X	0.004	0.012	
Y	0.015	0.015		Y	0.005	0.012	
Points Scored							
X	9	9		X	6	8	
Y	9	9		Y	6	8	
Average	9	9		Average	6	8	
Trials	1	0.5		Trials	0.5	0.5	
Total	10	9.5		Total	6.5	8.5	
Average Points		9.75		Average Points		7.5	
Evaluation							
Axes	Points			Trials	Points		
Direction	5			1 to 2	1.00		
Approach				3 to 4	0.50		
25%	1						
50%	2						
60%	3						
75%	4						

From the pre-course survey analysis we see that the students did not have much exposure to rapid prototyping technologies and remote operation previously, and most of undergraduate and graduate students thought that high quality learning can take place without the use of face-to-face interaction as well which is a positive sign for upcoming technologies to be used in the education environment, and students response was positive to the use of 3D for learning a skill or process. From student perception of post-course survey, students are comfortable and are more inclined towards web based education because they can access instructions, manuals and other documents online. The students also agree that instructor presence can be overcome by incorporating new technologies.

Based on the knowledge and hands-on experience with the simulator as well as machine and 3D visualization, the following are the insights from the post-course survey. Most students seemed to agree that they can learn more using multimedia to enhance skill as well as have a better quality education. Also the student's responses were affirmative in relation to the use of remote operation and enhanced perception using 3D visualization. They support the statement that multimedia systems like 3D and the simulation can enhance student learning. According to the survey, multimedia applications using 3D and simulations create interest in the student and help them learn more interactively and have an edge over the traditional face-to-face approach. Test results show not much significant difference between the experimental group and control group.

Conclusions

According to the survey, after experiencing with the alternative learning method, more students were able to accept this pedagogy instead of the traditional approach (i.e., face-to-face instruction). Moreover, the test results illustrate that there is no significant difference between the control and experimental groups. The findings from the aforementioned analysis provide an indication of how to effectively study the online bio-manufacturing laboratory problem in our future investigation.

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Bibliography

[1] Bresnahan, T., Brynjolfsson, E. & Hitt, L., 1999, "Information Technology and Recent Changes in Work Organization Increase the Demand for Skilled Labor," in M. Blair and T. Kochan, Eds., The New Relationship: Human Capital in the American Corporation, Washington, DC: Brookings

[2] Zeilhofer, H. F., 2009, Rapid manufacturing technologies for tissue engineering, International Journal of Oral and Maxillofacial Surgery, Volume 38, Issue 5,pp: 389-399.

[3] Y. Ravi Kumar* and C.S.P. Rao, T. A. J. R., 2009, Parametric modeling and simulation of rapid prototyping, International Journal of Rapid Manufacturing, Volume 1, Issue 1, pp. 65-87.

[4] itself., the fluid material. "Glossary." *CSA*. N.p., n.d. Web. 27 Mar 2010. <http://www.csa.com/discoveryguides/rapidman/gloss.php#ram>.

[5] Yan, Y., S. Li, et al., 2009, Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications, and Development Trends, Tsinghua Science & Technology, Volume 14, Supplement , pp. 1-12.
[6] Paul G. Ranky ., 2004, Interactive 3D Multimedia Cases for Engineering Education with Internet Support, A Technical paper from Society of Manufacturing Engineers
[7] Dessouky, Maged M, V.S, Bailey, Diane E, Rickel, Jeff., 2001, A methodology for developing a web-based factory simulator for manufacturing education, IIE Transactions (Institute of Industrial Engineers IIE Trans Netherlands, Volume 33, Issue 3, pp. 167-180.
[8] Yan Yongnian, L. S., Zhang Renji, Lin Feng, Wu Rendong, Lu Qing pin, Xiong Zhou, Wang Xiaohong .,2009, Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications and Development Trends, Tsinghua Science & Technology, Volume 14, pp. 1-12.
[9] http://www.foundryonline.com/ (FoundryOnline.com)
[10] http://www.me.psu.edu/lamancusa/rapidpro (Bill Palm and John S. Lamancusa, Penn State Learning Factory Rapid Prototyping website, last revised July 30, 2002)
[11] 2002, Rapid Prototyping Advances Medical Bone Implant Technology, Foundry Management & Technology, p. 96.
[12] Chua, C., S. Teh, et al., 1999, Rapid prototyping versus virtual prototyping in product design and manufacturing, The International Journal of Advanced Manufacturing Technology, Volume 15, Issue 8, pp. 597-603.
[13] Choi, S. H. and H. H. Cheung., 2008, A versatile virtual prototyping system for rapid product development, Computers in Industry Journal, Volume 59, Issue 5, pp. 477-488.
[14] Weber-Jahnke, J. H. and J. Stier., 2009, Virtual prototyping of automated manufacturing systems with Geometry-driven Petri nets, Computer-Aided Design Journal, Volume 41, Issue 12, pp. 942-951.
[15] University of Michigan Ann Arbor, Michigan e-Manufacturing, URL: http://wumrc.engin.umich.edu/workshop/
[16] “Future Engineers Face Competency Gap,” Ward's Auto World, March 1999, pg. 49
[17] Bresnahan, T., Brynjolfsson, E. & Hitt, L., 1999, “Information Technology and Recent Changes in Work Organization Increase the Demand for Skilled Labor,” in M. Blair and T. Kochan, Eds., The New Relationship: Human Capital in the American Corporation, Washington, DC: Brookings
[18] Bresnahan, T., Brynjolfsson, E. & Hitt, L., 2000, “Information Technology, Workplace Organization, and the Demand for Skilled Labor: Firm-level Evidence, Stanford University, Massachusetts Institute of Technology and University of Pennsylvania, Working Paper
[19] “Society of Manufacturing Engineers Refines Competency Gaps in Major Effort to Increase Effectiveness of Manufacturing Engineers,” The Society of Manufacturing Engineers' Manufacturing Education Plan: 1999 Critical Competency Gaps Report, URL: http://www.sme.org/
[20] Miller, S & Miller, K, 1999, “Using Instructional Theory to Facilitate Communication in Web-based Courses,” Educational Technology & Society, Vol. 2(3), pp. 106-114

[21] Althaus, S. L., 1997, “Computer-mediated communication in the university classroom: An experiment with online discussions. Communication Education, Vol. 46, pp. 158-174
[22] Connick, G. P., 1997, “Issues and trends to take us into the twenty-first century,” In T. E. Cyrs (Ed.) Teaching and Learning at a Distance: What it Takes to Effectively Design, Deliver and Evaluate Programs: No. 71. New Directions for Teaching and Learning, San Francisco: Jossey-Bass, pp. 7-12
[23] Hollandsworth, R., “Toward an Instructional Model for Asynchronous Instruction of Interpersonal Communications,” a paper presented at the 27th Annual EERA Meeting February 12, 2004.
[24] Report of the Subcommittee on Manufacturing Infrastructure: Enabling the Nation’s Manufacturing Capacity, April 1997.
[25] Ibrahim, N., Hambara A., and James, C., “2+2+2 Program in Manufacturing Information Systems: A Seamless Pathway to Engineering Education,” 29th ASEE/IEEE Frontier in Education Conference, November 10-13, 1999 San Juan, Puerto Rico.
[26] SME – Machine tools begin connecting to the Internet Manufacturing, 9/2001.