AUTOMATED ONLINE PROCESS TRAINING IN A VIRTUAL ENVIRONMENT

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Abstract

In this paper, we present the framework for an online virtual reality based learning environment for automated process training. The system has a lecture component that uses text-to-speech narrated lectures that are synchronized with interactive 2D and 3D graphics to introduce students to the concepts they will train on. The system also has a virtual environment (VE) that students navigate, in first person, where the practical training takes place. The VE contains accurate graphical models of the equipment on which training is sought, and is programmed with the logic of how the equipment is operated, and how it behaves. The system was used in various applications including training in the operation of Computer Numeric Control (CNC) milling and turning machines, welding machines, and industrial centrifugal pumps. In a pedagogical study that was done on the system, it was found that the virtual reality enhanced interactive online training produced similar student outcomes as compared to the traditional classroom lecture/lab approach.

Introduction

Training for the operation of industrial machinery and lab equipment is usually expensive, time consuming, and might require taking the equipment off-line. Furthermore, even with a knowledgeable instructor nearby to supervise the training, the equipment can still be hazardous to a novice trainee, and the novice trainee can be hazardous to the equipment. Thus there is a need to conduct, at least the initial phases of the training, more cheaply in a safe environment, where mistakes would not result in injury to personnel or damage to expensive equipment, without compromising the effectiveness of the training.

In order for the training to be effective and realistic, it is not enough for the students to learn by reading a book or a webpage, or listening to a lecture. Hands-on training on the use of the equipment is necessary in order to ensure that students are well versed in the necessary aspects of the equipment's operation and also, if needed, its maintenance. A computer generated virtual environment (VE) currently offers the best available option for achieving this training goal short of using the actual equipment[1]. The VE can be coupled with an online automated lecture on the use of the equipment, as well as step-by-step demonstrations of the various processes that need to be implemented on the equipment[2]. The term automated, as used here, means that the course can be implemented without any need for a human instructor[3]. This approach offers clear advantages over traditional classroom lectures, field training, or training manuals:

1- *Learners can learn at the time they choose.* The student can enter the virtual training environment at any time from a networked computer and choose to receive instruction in any topic of his/her choosing for as long as he/she wishes. In classroom-based training on the other hand, an entire group of students needs to convene at a specific time for a specific time to be instructed in a specific topic.

2- *Learners can learn at their own optimum pace*. The student can adjust the speed at which instruction is presented, can ask for more explanation, or go over a section of instruction material a second time. In classroom-based training on the other hand, the entire student group is presented with instruction at the same pace. The pace might be too fast for some students who will then tend to fall behind. The pace can also be too slow for other students who might then find the instruction boring or at least waste their time on re-learning things that they already understand.

3- *Multimedia enhanced highly interactive and engaging Training Environment.* The famous Chinese thinker Confucius is reported to have said: “I hear and I forget. I see and I remember. I do and I understand.” The online training should be designed to emphasize visual representation and interactivity. As opposed to training manuals, the rich multimedia content of the virtual training environment helps keep students interested. The high level of interactivity keeps students engaged in the learning process.

4- *The ability to learn and experiment within an inherently safe environment.* As opposed to working with real instruments, virtual instruments in the virtual reality environment are inherently safe and pose no danger of student injury, or equipment damage. The student is hence free to learn and experiment with the virtual instrument without instructor supervision. Furthermore, while there is no limit on the time that the student can spend on the virtual equipment, the student’s time with the actual equipment is often limited by the equipment’s availability, and the availability of an instructor that needs to be there to supervise the training.

5- *Minimizing training cost.* Since training on virtual instruments does not involve using any consumables, or human instructor resources, or equipment downtime, and since the training can be performed at the individual’s home or office which eliminates travel expenses, the cost for training can be substantially reduced.

6- *Increase training speed and fidelity*. Students can see inside a virtual instrument simply by making parts of the instrument semi-transparent (Figure 1) as opposed to a physical instrument where they would need to take the instrument apart in order to see its internal workings. Furthermore, the system can speed up non-interactive processes that usually take a long time on the actual equipment, such as machine warm up, to focus on more important training tasks.

7- *Display of visualization objects*. The virtual training environment can be used to display a multitude of visualization objects such as cutting planes, isosurfaces, streamlines, etc (Figure 2). The visualization objects make learning of spatially dependent concepts more efficient and effective.

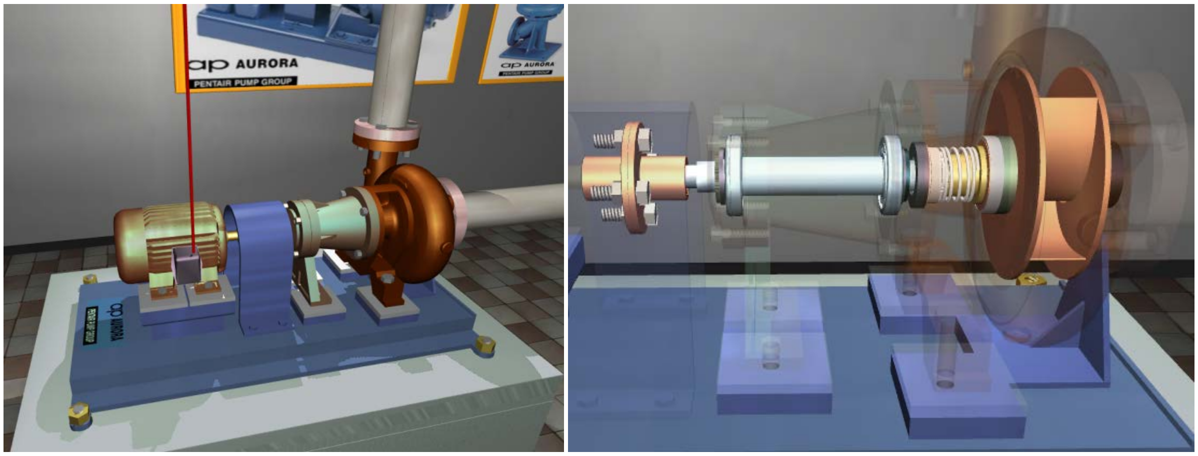


Figure 1. Virtual reality model of a centrifugal pump (left), showing the shaft assembly components (right).

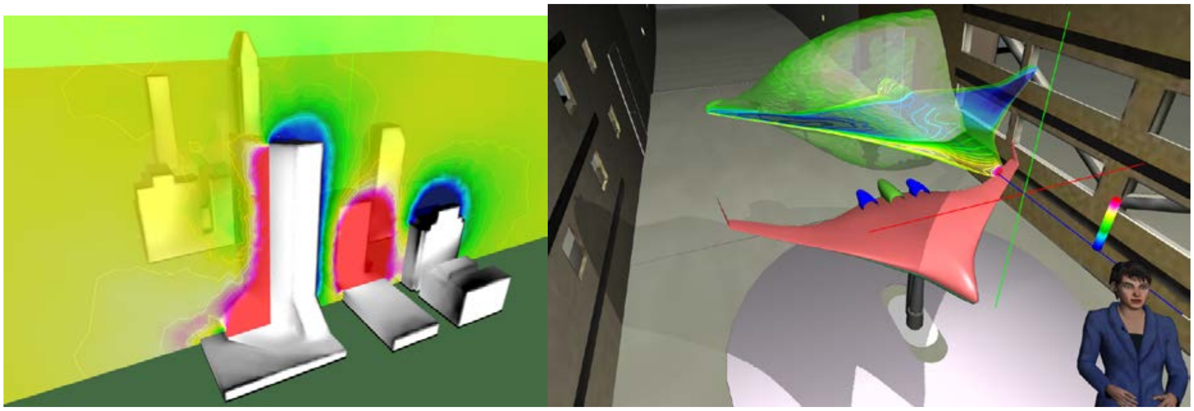


Figure 2. Visualization of a scalar field in a virtual environment using an interactive semi-transparent colored/contoured cutting plane (left) and an isosurface (right).

8- *Decision making training*. In addition to teaching students how to effectively operate the instruments, virtual training scenarios can also teach them decision making when faced with complex situations. Using a rule-based expert system[2,4], the user can interact using natural language with the computer generated characters that populate the virtual environment. This interaction can be accomplished with a microphone using speech recognition technology, or by using text. The user can also interact and collaborate with other users within the VE.

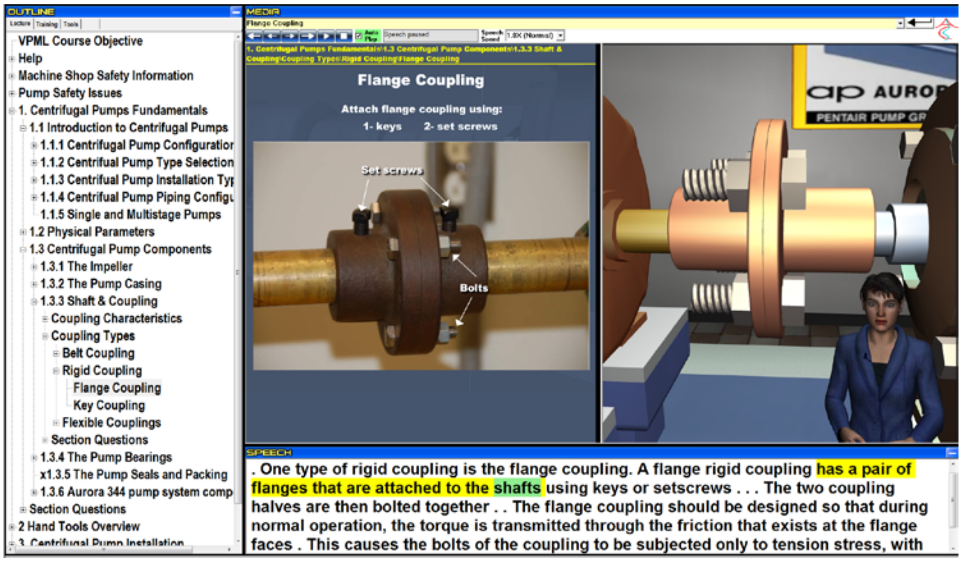
9- *Quickly adapt to new training needs*. If students need to train on a new instrument, they do not need to wait until they acquire the instrument. Students can use the VE to train in the use of equipment that has been added to the system's database even before these instruments are fielded.

10- *Easy course management*. A web-based course management system allows course administrators to get a real-time view of any student's progress within the course and to easily generate reports and statistics related to course usage. The course management system also controls the students' access to the course and records their registration information.

An automated interactive online course can accompany the VE and serve as the backbone of the learning environment (Figure 3). The course is delivered using text-to-speech technology by near-photorealistic animated virtual tutors[5]. The course is organized into a hierarchical tree outline of topics. The multimedia course items include pictures, movies, Flash animations, interactive Flash simulations, and virtual reality models to enhance the learning experience[6]. At the end of every course topic, the students are presented with a series of questions to test their comprehension of the material that was covered (Figure 4). Based on how the student scores in the post-topic questions and exercises, the tutor can either suggest that the student continue to the next topic, or go back over some of the previously seen material. The system can also answer natural-language user questions by searching the course material. Trainees can interact with the system in a multimodal way using a computer pointing device, specialized haptic devices, typed commands, or spoken commands.

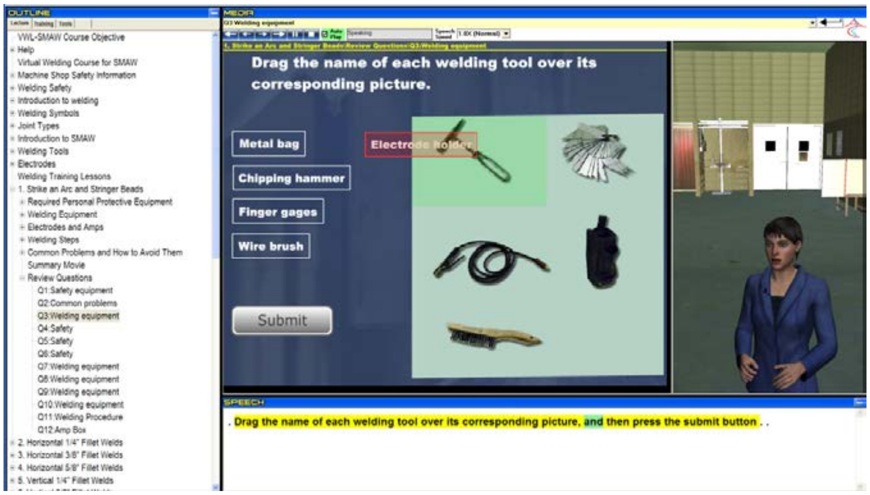
While the simulation of physical equipment within the VE clearly adds educational value as compared to 2D drawings of the same equipment, course designers should be careful not to cram elements into the VE that add no educational value by virtue of being displayed in 3D. In general, objects that need to be rotated, manipulated, opened, disassembled, or visualized should be viewed in 3D. On the other hand, objects that are inherently 2D such as 2 axis graphs, pictures, text, and equations should be displayed within a 2D environment (Figure 5). Furthermore, many simulations can more simply, cheaply and just as effectively be done in 2D using Flash or some other form of interactive content (Figure 6). Hence course designers should be judicious as to what they place within the VE, being careful to only place in the VE objects that add educational value by being viewed in 3D (Figure 7).

It is also the opinion of these authors that while VE should be used to visualize complex objects, it should not be used to navigate the course, or to move between course sections. Some course designers use rooms within the VE (such as in second life) that students access to navigate the course, with each room containing a course section, as a way of mimicking a school environment. While this might have entertainment or novelty value, it not only adds unnecessary development effort, but also makes course navigation confusing without increasing instructional effectiveness. In the opinion of these authors, a physical space should be modeled in the VE only to contain the objects that need to be visualized, or if the navigation and/or visualization of the physical space is itself an educational objective (Figure 8).



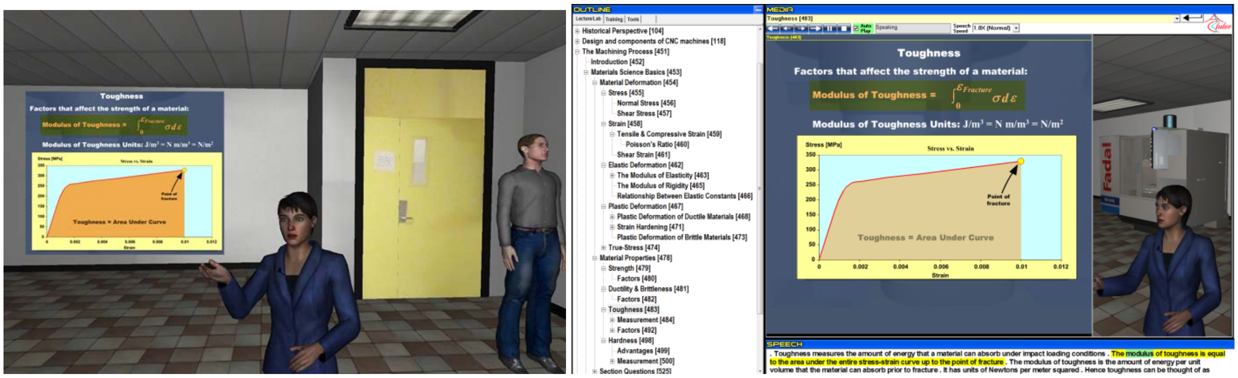
. One type of rigid coupling is the flange coupling. A flange rigid coupling has a pair of flanges that are attached to the shafts using keys or setscrews . . . The two coupling halves are then bolted together . . The flange coupling should be designed so that during normal operation, the torque is transmitted through the friction that exists at the flange faces . This causes the bolts of the coupling to be subjected only to tension stress, with

Figure 3. Snapshot of the course window for a centrifugal pump maintenance course. The virtual reality window on the right contains the virtual instructor and VE. The lecture window in the center is running an interactive Flash animated slide. The speech window at the bottom contains a text version of the virtual tutor's audio commentary on the slide. The course outline window on the left contains a hierarchical tree of the lecture topics.



. Drag the name of each welding tool over its corresponding picture, and then press the submit button . .

Figure 4. Example of a drag-and-drop question on welding equipment from an online welding course.


OUTLINE

Lecture/Lab | Training | Tools

- Historical Perspective [104]
- Design and components of CNC machines [118]
- The Machining Process [451]
  - Introduction [452]
  - Materials Science Basics [453]
    - Material Deformation [454]
      - Stress [455]
        - Normal Stress [456]
        - Shear Stress [457]
      - Strain [458]
        - Tensile & Compressive Strain [459]
          - Poisson's Ratio [460]
        - Shear Strain [461]
      - Elastic Deformation [462]
        - The Modulus of Elasticity [463]
        - The Modulus of Rigidity [465]
        - Relationship Between Elastic Constants [466]
      - Plastic Deformation [467]
        - Plastic Deformation of Ductile Materials [468]
        - Strain Hardening [471]
        - Plastic Deformation of Brittle Materials [473]
      - True-Stress [474]
    - Material Properties [478]
      - Strength [479]
        - Factors [480]
      - Ductility & Brittleness [481]
        - Factors [482]
      - Toughness [483]
        - Measurement [484]
        - Factors [492]
      - Hardness [498]
        - Advantages [499]
        - Measurement [500]
    - Section Questions [525]

MEDIA

Toughness [483]

Speaking

Speech Speed: 1.0X (Normal)

Toughness

Factors that affect the strength of a material:

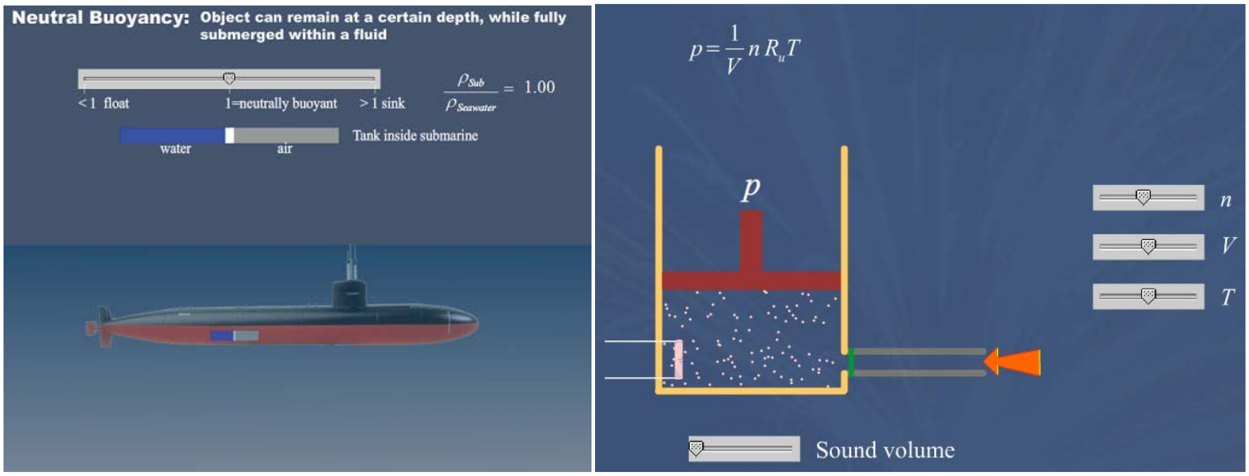
Modulus of Toughness = $\int_{0}^{\varepsilon_{Fracture}} \sigma \, d\varepsilon$

Modulus of Toughness Units: J/m³ = N m/m³ = N/m²

SPEECH

. Toughness measures the amount of energy that a material can absorb under impact loading conditions . The modulus of toughness is equal to the area under the entire stress-strain curve up to the point of fracture . The modulus of toughness is the amount of energy per unit volume that the material can absorb prior to fracture . It has units of Newtons per meter squared . Hence toughness can be thought of as

Figure 5. Displaying objects that are inherently 2D, such as graphs, text, or equations within the VE (left) does not add educational value, it is simpler and more effective to display these objects within a 2D environment like the Flash lecture slide in the middle of the shown course window (right).


Neutral Buoyancy: Object can remain at a certain depth, while fully submerged within a fluid

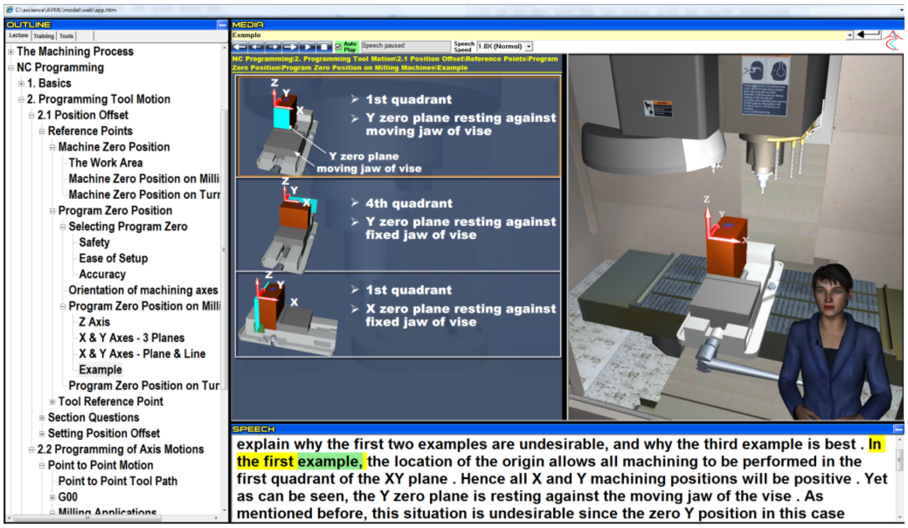
$$\frac{\rho_{Sub}}{\rho_{Seawater}} = 1.00$$

$$p = \frac{1}{V} n R_u T$$

Figure 6. 2D simulations of neutral buoyancy (left) and the ideal gas law (right) that will not be more effective if done in a 3D VE.

Figure 7. Static picture of a welding machine (left), and 3D interactive model of the same machine (right). In this case, clearly using the 3D interactive machine adds educational value that cannot be matched by a 2D picture or even a 2D interactive simulation.

Figure 8. Training environment for the operation of a wind tunnel showing the control room (left) and the electronics room (right). In this case, accurate navigation and visualization of the physical space is one of the educational objectives.



NC Programming\2. Programming Tool Motion\2.1 Position Offset\Reference Points\Program Zero Position\Program Zero Position on Milling Machines\Example

- 1st quadrant
- Y zero plane resting against moving jaw of vise

- 4th quadrant
- Y zero plane resting against fixed jaw of vise

- 1st quadrant
- X zero plane resting against fixed jaw of vise

explain why the first two examples are undesirable, and why the third example is best . In the first example, the location of the origin allows all machining to be performed in the first quadrant of the XY plane . Hence all X and Y machining positions will be positive . Yet as can be seen, the Y zero plane is resting against the moving jaw of the vise . As mentioned before, this situation is undesirable since the zero Y position in this case

Figure 9. Lecture item from the AVML on workpiece setup on a milling machine.

Training Applications

The above described system was used to effectively develop several learning environments, some of which are described subsequently:

1- *The Advanced Virtual Manufacturing Lab (AVML)*: The AVML[7-10] (Figure 9) is a complete system for training in Computer Numeric Control (CNC) milling and turning machine operation and Numeric Control (NC) programming. It includes a comprehensive course on machine shop safety, design and components of CNC machines, material science basics, machining fundamentals, cutting tools, and NC programming. The AVML also provides interactive step-by-step training in various machine operations. The VML includes interactive virtual reality models of a FADAL VMC 3016L 3-axis milling machine (Figure 10), a HAAS Super VF-2 5-axis milling machine, and a HAAS SL-20 turning machine (Figure 11). The machine models include an NC code emulator to execute NC code on the virtual machines including commands for moving the cutting head, changing travel speed, changing rotation speed, controlling coolant flow, and changing the cutting tool. The machine model also incorporates a solid modeling capability that allows the virtual machine to cut a virtual part by subtracting the volume of the tool from the volume of the part in real time (Figure 12). The system also calculates the forces on the tool during the cutting of the virtual part to predict tool breakage events (Figure 12).

2- *The Virtual Welding Lab (VWL)*: The VWL (Figures 4, 13) teaches the theory and practice of welding processes. The VWL includes four welding processes: Shielded Metal Arc Welding (VWL-SMAW), Gas Metal Arc Welding (VWL-GMAW). Flux Cored Arc Welding (VWL-FCAW), and Gas Tungsten Arc Welding (VWL-GTAW) (Figures 7, 14).

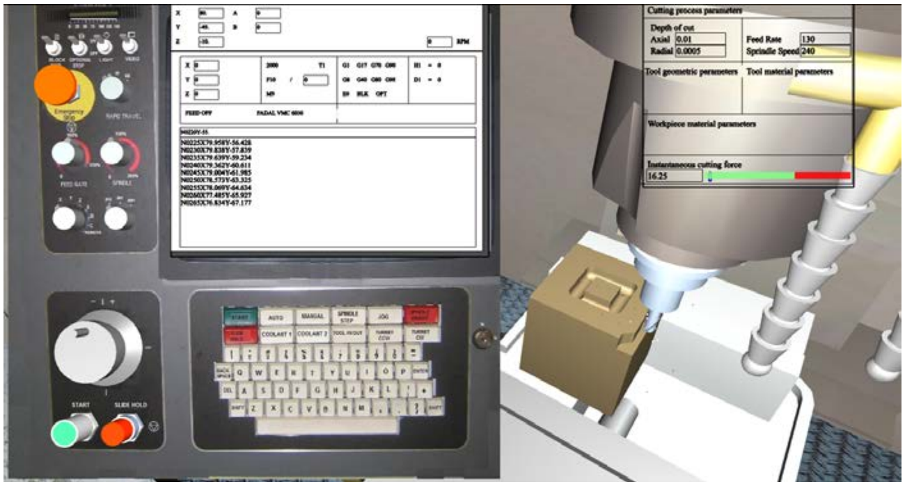
3- *The Virtual Centrifugal Pump Lab (VCPL)*: The VCPL (Figure 3) teaches about the selection, installation, operation, and maintenance of centrifugal pumps. The VCPL includes a detailed model of a typical centrifugal pump that students can use to visualize the internal pump components during pump operation (Figure 1).

Measuring Effectiveness

The effectiveness of the aforementioned Advanced Virtual Manufacturing (AVML) course was assessed in an undergraduate and in a graduate level engineering course[11]. No significant difference was observed in student outcomes between students who learned the lecture material using the AVML and students who learned using the traditional classroom lecture approach. The mean score for students

Figure 10. Interactive models of a FADAL VMC 3016L 3-axis milling machine.

Figure 11. Interactive model of a HAAS Super VF-2 5-axis milling machine (left), and a HAAS SL-20 turning machine (right).



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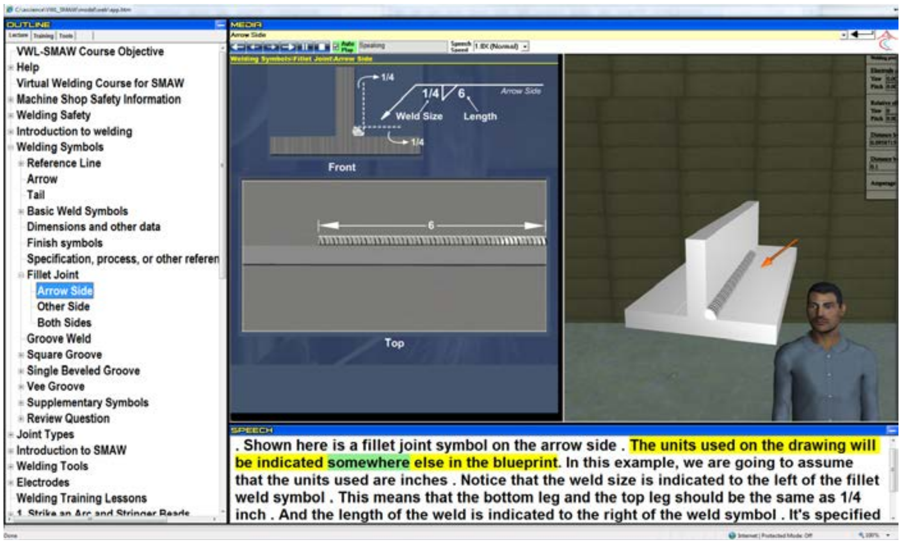
N0225X79.958Y-56.428
N0230X79.838Y-57.839
N0235X79.639Y-59.234
N0240X79.362Y-60.611
N0245X79.004Y-61.985
N0250X78.573Y-63.325
N0255X78.069Y-64.634
N0260X77.485Y-65.927
N0265X76.834Y-67.177
```

Cutting process parameters
Depth of cut
Axial 0.01
Radial 0.0005
Feed Rate 130
Spindle Speed 240
Tool geometric parameters
Tool material parameters
Workpiece material parameters
Instantaneous cutting force 16.25

Figure 12. Virtual machining of a work piece on a 3-axis milling machine. The machine controller View, on the left, shows the current NC-code line that is being executed. The machining monitor, on the top right, shows the machining parameters and estimated values of the cutting forces.



. Shown here is a fillet joint symbol on the arrow side . The units used on the drawing will be indicated somewhere else in the blueprint. In this example, we are going to assume that the units used are inches . Notice that the weld size is indicated to the left of the fillet weld symbol . This means that the bottom leg and the top leg should be the same as 1/4 inch . And the length of the weld is indicated to the right of the weld symbol . It's specified

Figure 13. Snapshot of a lecture topic from the VWL on interpreting welding symbols.

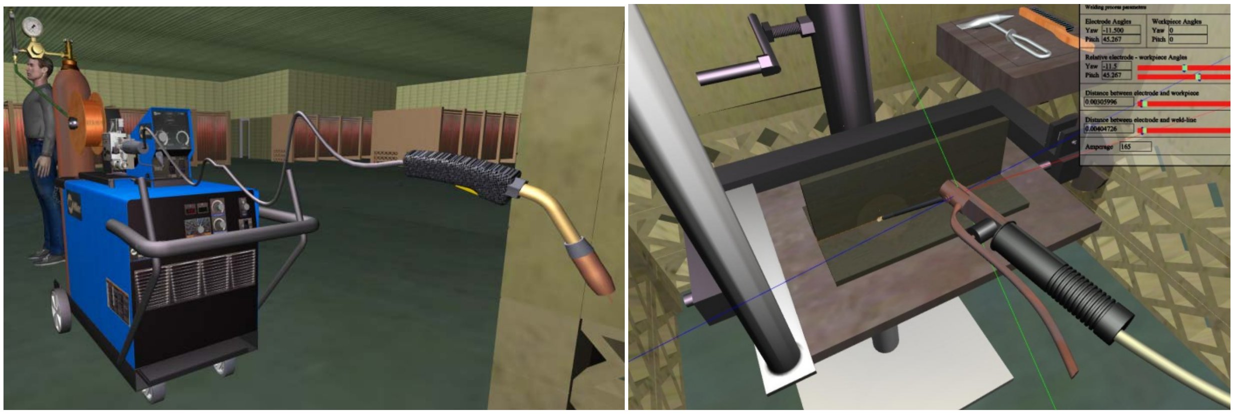


Figure 14. Snapshots from the VWL show a virtual welding machine for Gas Metal Arc Welding and Flux Cored Arc Welding (left) and a demonstration of virtual shielded metal arc welding of a workpiece (right).

who learned the lecture material in a traditional classroom setting was 88.3% with a standard deviation of 9.0%, while the mean score for students who learned solely using the fully automated online course was 90.0% with a standard deviation of 10.5%. This shows that a fully automated interactive online course can be an effective substitute for classroom teaching in either a lecture or lab setting. The cost advantage of the automated class renders it superior to traditional classroom teaching. It is interesting to note that in the above mentioned study when the AVML was used in conjunction with classroom instruction, student outcomes improved significantly to a mean of 99% with a 3.2% standard deviation.

Conclusions

The framework of an online interactive automated course delivery system that includes an interactive virtual environment for training was presented. A pedagogical value study of the system concluded that the system was on par with the traditional classroom lecture/lab approach in terms of teaching effectiveness. The systems implementation in a computer numeric control course, a welding course, and a pump maintenance course was described.

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Biographical Information

Mr. Hatem Wasfy is the President of Advanced Science and Automation Corp. (ASA), a company that specializes in the development of online virtual learning environments and advanced engineering simulations. He has helped design several interactive learning environments that include a CNC machining course, a centrifugal pump maintenance course, an undergraduate physics course, and a welding course. He received a B.S. (1994) and an M.S. (1996) in mechanical engineering from the American University in Cairo. His research interests include advanced learning systems, cavitation modeling, computational fluid dynamics, internal combustion engine modeling and design, and AI rule-based expert systems.

Tamer Wasfy received a B.S. (1989) in mechanical engineering and an M.S. (1990) in materials engineering from the American University in Cairo, and an M.Phil. (1993) and Ph.D. (1994) in mechanical engineering from Columbia University. He worked as a research scientist at the Department of Mechanical Engineering, Columbia University (1994-1995) and at the University of Virginia at NASA Langley Research Center (1995-1998). Wasfy is an Associate Professor at the Mechanical Engineering Department at Indiana University-Purdue University Indianapolis (IUPUI). He is also the Founder and Chairman of Advanced Science and Automation Corp. (founded in 1998) and AscienceTutor (founded in 2007). His research and development areas include flexible multibody dynamics, finite element modeling of solids and fluids, fluid-structure interaction, belt-drive dynamics, tires mechanics/dynamics, ground vehicle dynamics, visualization of numerical simulation results, engineering applications of virtual-reality, and artificial intelligence. He authored and co-authored more than 70 peer-reviewed publications and gave more than 65 presentations at international conferences and invited lectures in those areas. He received two ASME best conference paper awards as first author. He is the Software Architect for the DIS, IVRESS, and LEA software systems, which are used by industry, government agencies, and academic institutions. He is a member of ASME, AIAA, SAE, and ASEE.

Jeanne Peters received a B.A. in math/computer science from the College of William and Mary. She worked at the NASA Langley Research Center in Hampton, Va. for more than 20 years as a Senior Programmer/Analyst for George Washington University, University of Virginia, and Old Dominion University. She co-authored more than 70 journal and conference papers in the areas of computational mechanics, finite element method, shells/plates, composite material panels, and tires. She has also worked on numerous projects to create advanced engineering design and learning environments, which include multimodal user interfaces for space systems. As Vice President of Information Technology, Peters directs the development of advanced virtual reality applications, including scientific visualization applications and web-based multimedia education/training applications.

Hazim El-Mounayri is an Associate Professor of M.E. and the Co-director of the Advanced Engineering and Manufacturing Laboratory (AEML) at IUPUI. The AEML is currently conducting research in virtual manufacturing and intelligent (multiscale) machining, which aims at developing the Advanced Virtual Manufacturing Laboratory for Training, Education, and Research (AVML), an innovative e-learning tool for educating students and training the next generation workforce in sophisticated technology and its underlying theory. The core technology is being used to develop online courses that incorporate both lecture and lab components. He teaches capstone design and has mentored several projects for industry and other sponsors. He has been very active in undergraduate research. Among the multidisciplinary undergraduate research projects he mentored, two consisted of assessing the usability and pedagogical value of the AVML tool. His teaching and mentoring performance has won him several teaching/mentoring excellence awards, including the 2008 and 2010 TERA awards for teaching excellence. He has published more than 60 technical papers in renowned peer-reviewed journals and technical conferences in his field and gave presentations at various national and international conferences, including ASEE. He is a member of ASME, ASEE, and SME.