

## VIRTUAL MANUFACTURING LEARNING ENVIRONMENT

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### Abstract

A Web-based virtual manufacturing learning environment is presented. It integrates virtual reality, accurate physics-based machining simulation, and intelligent agents acting as virtual tutors to provide: (a) interaction with fully-functional virtual machine tools, including real-time machining of parts, (b) training on key operating procedures, and (c) virtual tutors that collaborate to guide, supervise, and certify the user in machining operations. This enables colleges to easily and inexpensively provide students with effective, safe, and highly accessible training on advanced machine tools.

### Introduction

Economic and social factors have contributed to increased demand for advanced manufacturing training. Manufacturing remains the most powerful engine of economic growth and innovation. The manufacturing industry accounted for 14% of the national Gross Domestic Product (GDP) in 2001 [1]. Manufacturing spawns more additional activity and jobs than any other economic sector. Every \$1 of final demand for manufactured goods generates an additional \$0.76 in products and services from non-manufacturing sectors [2]. Faced with mounting global competitive pressure, US manufacturers have to make significant productivity gains. Those gains require a highly skilled workforce that is trained in advanced manufacturing technology. Most potential manufacturing workers do not have access to state-of-the-art manufacturing labs that can provide such training.

According to a recent report from the Center for Workforce Success, with the retirement of the baby-boom generation, American manufacturers face a severe shortage of men and women to run tomorrow's factories. One of the most protracted problems that employers face is the lack of new skilled workers to operate their high-tech manufacturing plants [3]. The aging population and the resulting shortage in skilled manufacturing workers is a major socio-economic driver that will result in increased demand for advanced manufacturing training.

In response to the above social and economic drivers, the number of manufacturing education programs offered by institutions of higher learning in the US is growing. The number of Industrial/Manufacturing Engineering Bachelor degrees grew by 12.84% between 2002 and 2003 and overall enrollment grew by 4.2% [4]. In a survey conducted by the Society of Automotive Engineering (SAE) a vast majority of respondents (94.1%) indicated that there is a strong need for more manufacturing engineering programs in the US [5].

Modern state-of-the-art CNC machines are expensive to buy and maintain. Universities and community/technical colleges who would like to have a state-of-the-art manufacturing lab have to spend hundreds of thousands of dollars on setting it up and tens of thousands of dollars on maintaining it. Moreover, to remain current, renovation must occur every few years. For example, recently the University of Washington, which already had a manufacturing lab, budgeted \$600,000 for the renovation of its lab [6].

Despite making significant investments, access remains limited at universities and community/technical colleges who have advanced manufacturing labs. Currently, students are introduced to CNC machines in small groups and can only operate the machine for a short time due to limited lab hours. It is very difficult (if not impossible) to bring a student, in a semester or two, to a level where he/she would feel comfortable operating CNC machines without

supervision. Typically, academic institutions will never take the risk of unsupervised operation of machines by students.

There is a need for a solution that enables universities and community/technical colleges to provide or complement education and training on state-of-the-art advanced CNC machines while optimizing the resources spent on building, maintenance, and renovation of advanced manufacturing labs every few years. The solution must provide better access to advanced manufacturing training and increase its safety, effectiveness and completeness.

Virtual environments (VEs) can provide a safe, cost-effective, and flexible environment for training. Fueled by recent strides in computer CPU and graphics cards speeds, VEs are increasingly becoming more realistic. Accordingly, VEs are being increasingly used in training applications. Recent applications of VE based training include: training for operation of: engineering facilities [7], maintenance simulators [8], medical procedures training [9,10], and military operations training [11]. Motivated by the advantages of VE based training, several research groups and commercial companies developed virtual CNC machines that attempted to meet some of the above objectives.

Suh *et al.* [12] developed a web-based virtual CNC machine that includes geometric and kinematic models of the machine and that uses the VRML COSMO player along with JAVA-applets. The user interacts with the machine through a separate 2D panel not through the machine controller in the VE as they would in the actual machine.

Ong *et al.* [13,14] developed a web-based interactive manufacturing teaching module that uses VRML and JAVA applets. A G-code interpreter is implemented using a JAVA-applet that controls VRML scene to produce the tool motion corresponding to the G-code program. The VRML ElevationGrid object was used to model the work-piece. The heights of the ElevationGrid are changed based on the intersection of the surface with the tool. A simple average cutting force model based on the power required to remove a unit volume of material was used. The system does not have a machine controller simulator capability and thus does not allow the user to interact with, program, and operate the virtual machine in the same way as the actual machine. Luo *et al.* [15] developed a web-based virtual milling machine that combines a geometric model for the machine with stitched images for the rest of the workshop and that uses the aforementioned ElevationGrid VRML technique. Kong *et al.* 2002 [16] also developed a web-based virtual milling machine that uses the aforementioned ElevationGrid VRML technique. Both systems have more or less the same limitations as the previous Ong *et al.* system.

Lin *et al.* [17] developed a virtual-reality CNC training prototype system driven by the WorldToolKit from Sense8 and consisting of five modules: training task-planning, machine simulator, performance evaluation, instruction, and interface. The system focuses on basic manual operations and doesn't have a G-Code interpreter and the machining of parts is not accounted for.

Chang *et al.* [18] developed haptic and aural rendering for a 5-axis virtual milling machine. Haptic rendering was used so that the user can feel the cutting forces and surface roughness. The analytic cutting force model developed by Abrari and Elbestawi [19] was used. Aural rendering was done using Microsoft DirectSound functions. The cutting force was used to determine the amplitude of the cutting sound and the spindle speed was used to determine the frequency. The system focuses on the haptic and aural rendering of the machining process and doesn't model the controls or other aspects of the machine.

Ustarroz *et al.* [20] developed VIRTOOL – a virtual learning environment for milling machines. Virtool does not have a machine controller simulator capability and thus does not allow the user to interact with, program, and operate the virtual machine in the same way as the actual machine.

Denford Ltd. [21] developed a virtual training environment for micro milling machines, not full production models. The 3D real-time work-piece solid model is not accounted for. The fidelity of interactivity is low and the student interacts with the machine and its controls through separate windows in the program and not directly in the virtual environment as they would in the actual environment. The machine dynamics and the 3D real-time part solid model are not accounted for. Another company, Delmia [22] offers CNC machining verification modules that include fast solid modeling for predicting the work-piece geometry during the cutting process. It doesn't offer training capabilities and is mainly targeted towards validation of NC code.

None of the existing systems includes capabilities for virtual tutors and only the system from Lin et al. had some knowledge capture capability for a few basic operations. The visual quality generally ranges from medium to low while interactivity is limited and the user can't interact with, program, and operate the virtual machine in the same way as the actual machine. While few of the systems account for some of the physical aspects of the cutting process, the accuracy is low and none accounts for aspects that add realism such as chip formation and flying.

In this paper, the Advanced Virtual Manufacturing Lab (AVML) will be presented. The AVML is a virtual manufacturing learning environment that surpasses the previously reported virtual CNC milling machines in the following five aspects: visual and audio fidelity of the virtual machine, naturalness of interactivity, accuracy of modeling the cutting process, use of virtual tutors, and knowledge capture and dissemination. The software currently includes a 3-axis CNC milling machine and will eventually include other types of manufacturing machines such as production-grade 5-axes milling machines and CNC lathes.

### AVML Characteristics

We believe that the following are the most important characteristics of an advanced manufacturing training VE solution in terms of what end-users want: visual quality; fidelity of interactivity; accuracy of physical modeling of the machining process; effective use of virtual tutors; ease of access; and low cost.

#### *Visual Quality*

Visual quality is an important characteristic because for the training to be effective, a virtual manufacturing learning environment must accurately emulate a physical manufacturing lab. The high fidelity of the virtual environment should give the student a visual effect almost as realistic as being in the actual lab. A visually realistic virtual machine should look and sound almost the same as the physical machine. All existing virtual CNC machines fall far short from that goal. In the AVML, the virtual CNC machine is near-photorealistic and produces near-real sounds including machining sounds.

The AVML is driven by IVRESS [23], an object-oriented scene-graph based virtual-reality display engine. The machine model (Figure 1) is a hierarchical scene-graph that includes the machine geometry and the machine control widgets. The machine geometry consists of textured surfaces of the various machine parts. The machine parts were modeled in Pro-Engineer Wildfire® as solid models and then exported in VRML format as tessellated surfaces. The surfaces were textured using photographs of the actual machine to produce a near-photorealistic model of the machine. In addition, to the machine a work-piece preparation area (Figure 2) and the lab room (Figure 3) were modeled. The work-piece preparation area allows the user to select the cutting tools, place the parallels in the work-piece fixtures, use the mallet to secure the work-piece on the fixture and define the dimensions of the raw work-piece block. The lab room will eventually contain other CNC machines such as a CNC lathe. In addition, the user can make parts of the machine such as the sheet-metal enclosure semi-transparent or hide parts of the machine in order to more clearly see the motions of the other machine parts (Figure 4).

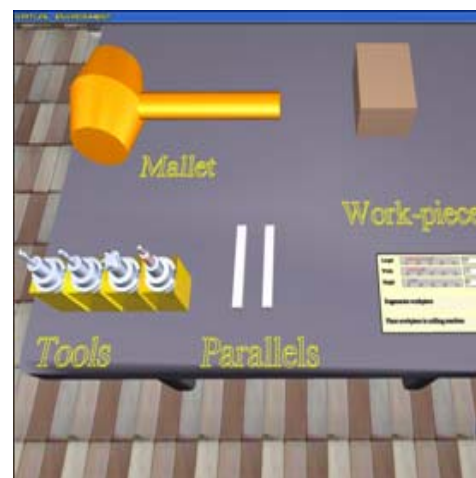


Fig 1. CNC machine virtual model



Fig 3. Virtual manufacturing lab and two intelligent tutors (screen tutor and environment tutor)

Fig 2. Work-piece preparation area



Fig 4. The virtual tutor makes the machine semi-transparent to show the base during a lecture

*Fidelity of Interactivity*

Most virtual CNC machines use separate 2D windows to model the machine controller. Some have a 3D immersed controller that is not photorealistic and does not have the same shape of knobs, buttons, and switches as the actual machine. Using the AVML, students are able to interact with the virtual CNC machine similarly to how they would interact with it in the real manufacturing lab. In the AVML, the machine controller (Figure 5) and machine software screens (Figure 6) are almost identical to the actual CNC machine. A software emulator models the software screens, which are displayed on the screen of the machine controller. An NC code interpreter allows users to program the virtual machine in the same way they would program the actual machine. Also, the control knobs, buttons, and switches are near-photorealistic. All the buttons and knobs in the machine controller are fully functional and users can interact with the virtual machine in the same way they would interact with the actual machine.



Fig 5. Machine controller

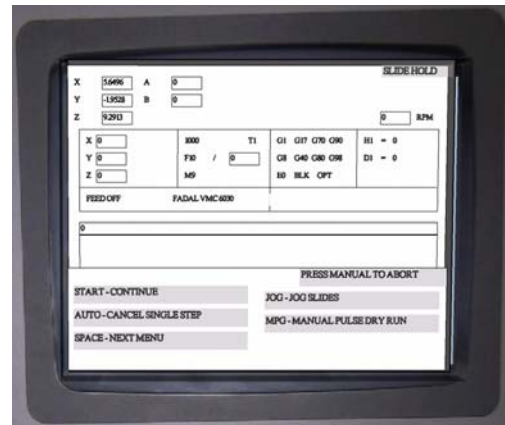


Fig 6. A typical machine software screen (program start screen)

The AVML provides better than “computer-game” quality navigation in the VE that uses a physics-based dynamic motion model along with a penalty-based frictional contact model. Most previous CNC machines use COSMO player which provides VRML type navigation that is purely kinematic and that does not include effects such forces, acceleration, and friction.

Previous virtual CNC machines did not include the machine sounds including the cutting sounds. Chang et al. 2001 [18] only included a rough model of the cutting sounds. The AVML produces near-realistic machine sounds such as

cutting, spindle rotation, switching on/off the machine, toggling the various controls (buttons, switches, and knobs), opening/closing the machine door, tool change, etc.

### *Accuracy of Physical Modeling of the Machining Process*

The machining process is inherently a physical process that involves cutting speeds, feed rates, material removal, etc. The machining physical effects should be accurately modeled so the student gets the same results in the virtual lab that they would get in the physical lab. Previous virtual machines only included the geometric aspect of the cutting process. The accuracy of the geometric modeling varies from the very accurate system of Delmia Inc. to the less accurate VRML ElevationGrid-based geometric modeling technique. The AVML geometric modeling uses the ACIS™ solid modeling engine [24] which is similar to the Delmia's system in terms of accuracy and speed. Among the systems that include the physical aspects of the cutting process, Chang et al. [18] and Ong et al. [14] include a rough average cutting force model. Other physical aspects such as instantaneous cutting forces, tool deflection, surface errors, and surface roughness are generally not modeled accurately or not modeled at all. The AVML includes an accurate artificial neural network (ANN) instantaneous cutting force model. The force model is used to predict tool deflection, surface errors, and surface roughness. Also, the maximum stress at the root of the tool is compared to the yield stress to predict the onset of tool breakage.

The AVML also models other physical aspects of the cutting process that enhance the realism of the learning environment such as chip formation and flying (Figure 7). The spindle-speed and cutting force are used to calculate the size, flying speed, and frequency of chips.

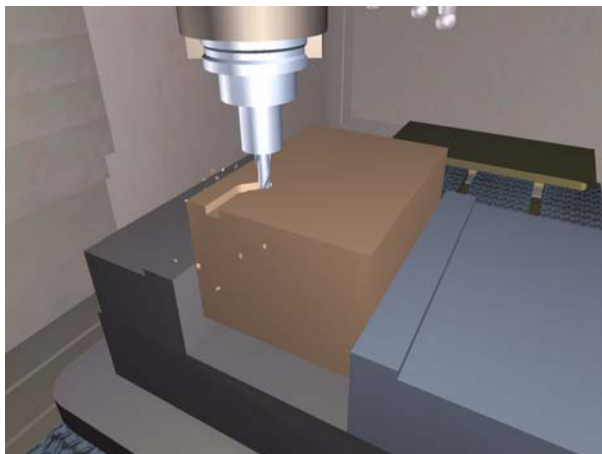


Fig 7. Snapshot of machining of a work-piece showing the flying chips

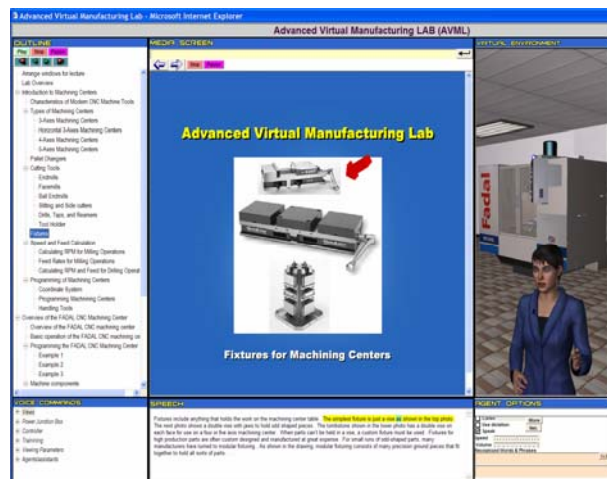


Fig 8. AVML Web-based interface

### *Effective Use of Virtual Tutors*

In order to quickly begin using the system and to make the training more effective, intelligent virtual tutors that act as lab assistants to guide and supervise the user are integrated seamlessly with the learning environment (Figure 3). An "always on top of the screen" virtual tutor (screen tutor) is always visible and provides guidance and answers to the user's questions as well as structured multi-media lectures. In addition, an intelligent virtual assistant in the environment directly assists the user by demonstrating the correct procedure to perform the required process steps.

The two virtual tutors collaborate to help the user. For example, when the user needs help, he asks the screen tutor by speaking or typing a natural language question. The screen tutor will say the answer and display any multi-media, which support the answer. The screen agent will also command the assistant in the environment to actually do a demonstration if necessary. Visual cues such as 3D flashing arrows are used in addition to the agent in the environment pointing to the correct objects in the environment. The virtual tutors are fully animated and interact in a natural way, including arm motions, walking, gestures, emotional facial expressions, and lip-synched speech.

The intelligent virtual tutors use a Natural Language Interface (NLI) to communicate with the user. The NLI enables two-way communication with the user in natural-language speech (and/or written text). Thus the user doesn't have to memorize commands and can communicate naturally with the tutors in the environment. The NLI accomplishes natural-language understanding by using LEA's hierarchical rule-based expert system engine [25] to convert the user's natural-language commands to script that can be sent to the AVML. The NLI communicates with the user by sending output speech to a speech synthesis engine, as well as by changing the visual state of objects in the AVML.

The traditional knowledge capture method of relying on operating manuals fails to capture the dynamic and time-dependent aspects of operating CNC machines. The AVML allows the instructor of a manufacturing class to easily and quickly integrate lecture content into the virtual manufacturing learning environment and synchronize it with training activities. One of the capabilities of LEA is the unstructured knowledge base engine. The unstructured knowledge consists of "knowledge items" that can be arranged by the instructor in any order to form a lecture. A knowledge item is a tagged short HTML segment with embedded multimedia content. A knowledge-base file is simply a collection of knowledge items. LEA allows multiple knowledge-base files to be loaded. A file is loaded using its URL. Thus the knowledge base can be anywhere on the Web. The Web-based interface consists of six resizable and moveable windows (Figure 8): a VE window, a multimedia instruction window, a speech window, a hierarchical lecture outline window, a hierarchical list of voice commands window and an agent-options window. LEA also includes a search capability in order to be able to answer the user's natural language questions from the unstructured knowledge-base.

LEA also includes a structured hierarchical process knowledge capability that allows training users on operating procedures such as machine start-up; machine shut-down, G-code loading from disk, and running an existing G-code. Each process can consist of a set of steps as well as other sub-processes. Each process and step can have pre- and post- constraints. Pre-constraints have to be satisfied before the step/process can be started. Post-constraints have to be satisfied before the step/process is completed. The virtual tutor can disseminate process knowledge using one of the following training modes. The desired mode is triggered using a natural-language user's command interpreted using the LEA rule-based expert system. The training modes are:

1. *Process Tutor*. The screen tutor instructs the environment tutor to perform the process steps while the user is watching. The user can pause/resume, repeat (go back) a step, or skip a step.
2. *Process Info*. This tutor mode will only recite the process steps to the user.
3. *Process Guide*. The tutor guides the user step by step through the process. The tutor will not go to the next step until the user says a command such as "continue" or "proceed." The user has to perform each step. The tutor checks the process constraints to determine if the user performed the step correctly. If a constraint is violated, then it instructs the user to repeat the step. If the user does not perform the step correctly three times in a row, then the screen tutor instructs the environment tutor to intervene and demonstrate the correct procedure by performing the step for the user.
4. *Process Supervisor*. The tutor instructs the user to perform the process. At the end of each sub-process the user lets the tutor know that s/he is done. At that point the tutor checks the sub-process constraints. If no mistakes were detected, then the tutor instructs the user to perform the next sub-process. If mistakes are detected, then it lists the mistakes and instructs the user to repeat the sub-process.
5. *Process Certification*. This mode is similar to the process supervisor mode except that the user performs all the process steps and the tutor keeps track of any mistakes the user made. Finally, the user indicates that he completed the process and the tutor informs the user of the mistakes made in the process. If no mistakes are detected then the tutor certifies the user in this process, otherwise additional training is suggested.
6. *Intelligent Virtual Assistant*. The user asks the tutor to perform a process. The tutor performs the process while the user can either watch the agent or do something else. This facility can be used, for example, to simulate interaction with a virtual team in a virtual manufacturing cell.

### *Ease of Access*

The AVML can be used anywhere there is access to a high-speed internet connection or it can be easily distributed on a CD when a high-speed internet connection is not available and can run on existing PC hardware, including notebook computers. Unlike manufacturing labs with limited lab hours and required supervision, any number of students and educators from various geographic locations can access the AVML at any time. The AVML can be used to provide hands-on training on the operation of CNC machines. The students can safely experiment with the virtual machines and test operating procedures and CNC programs without risk of damaging expensive equipment

and facilities or injury. Hands-on training and experimentation enhance students learning and retention and increase students creativity and problem-solving capabilities. The AVML provides a safe virtual environment enabling accelerated learning of advanced manufacturing technology and allowing unsupervised usage of virtual CNC machines.

The AVML framework is modular and object-oriented in order to allow for component reuse and ease of integration of new capabilities and sub-components into the environment. The AVML framework allows various groups to almost independently develop the various components of the virtual machine. In addition, the AVML runs on any platform equipped with an OpenGL graphics capability including Windows™ 2000/XP, LINUX and UNIX PCs and Notebook computers. It also readily runs on multi-screen stereoscopic immersive virtual reality facilities, which include head-tracking, such as the CAVE™ as well as the single screen workstations.

### *Cost*

The cost of a VE solution must be a small fraction of the current cost for building and maintaining a state-of-the-art manufacturing lab. We estimate that in order to be successful, the cost per student should be less than that of an average manufacturing textbook. A search on Amazon.com showed a price of \$124.95 for a typical undergraduate manufacturing textbook [26]. We estimate that the cost of the AVML per student will be less than half that amount.

The AVML runs on existing computer hardware. Thus even small colleges can provide CNC machining training without investing a lot of money to setup a CNC machine lab. Even for large colleges, there could be budget limitations that prevent the initial investment (especially, for sophisticated machines) or the subsequent upgrading to keep up with the changing technology. In addition, the AVML saves money on consumables such as tools and work-pieces. In addition, the AVML object-oriented framework allows for component reuse and ease of integration of new machine tools into the environment. This minimizes the effort and cost of expanding the virtual advanced manufacturing lab with new machine tools and maximizes the opportunity of collaboration between research institutions as well as between academia and industry.

### **Conclusion**

The AVML, a prototype Web-based virtual manufacturing learning environment for was presented. For universities and colleges that already have a manufacturing lab, the AVML can complement and enhance their existing manufacturing labs. For example, it can shorten the time it takes for students to become familiar with CNC machine tools. Students and instructors can test NC-Code on the virtual machine before running it on the actual machine. The AVML can protect the investment in expensive machines by making sure there are no errors that would result in a badly machined part or damage to the machine. Using the AVML's unstructured and structured knowledge management capabilities, manufacturing instructors can easily customize and update the training.

The AVML enables access to a virtual advanced manufacturing lab by universities and four year colleges that do not have a full-blown manufacturing program but have a related program such as Mechanical Engineering and would like to provide their students with sufficient knowledge and skills in manufacturing, including CNC machining. For example, Mechanical Engineering departments in engineering schools with no program in manufacturing are usually unable to provide the manufacturing background needed to create "intelligent" designers and highly marketable engineers in the manufacturing/machining industry. Many mechanical engineers end up working in jobs that directly or indirectly involve manufacturing.

Community and technical colleges offer manufacturing and industrial technology programs but often cannot afford to spend hundreds of thousands of dollars on building a state-of-the-art manufacturing lab and tens of thousands every year on maintaining it. As a result, many students only get to see a CNC machine in textbooks and do not get an opportunity to interact with or program one. The AVML will enable access to a virtual manufacturing lab that would provide such an opportunity.

The AVML object-oriented framework minimizes the effort and cost of adding new machines. The framework also enables AVML objects to reside on different local or remote networked machines so that different universities, companies, and institutions can easily build the AVML machines models yet they can all be accessed from

anywhere on the Internet. This will foster more collaboration between academia and industry so that, for example, a university can provide custom virtual training on specific advanced machine tools that are used by local industry.

Manufacturing companies (especially, those in mass production) tend to use CNC machines with large beds, pallet changers, and other special features. Students do not normally have access to training on such machines. Thus, the next research and development activities include expanding the AVML prototype with additional types of machines such as a production-grade 5-axes milling machine with automatic pallet changer (APC) and a CNC lathe.

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