AC 2009-1793: ENHANCING MACHINE-SAFETY EDUCATION THROUGH THE USE OF VIRTUAL MACHINERY

Darrell Wallace, Youngstown State University
Darrell Wallace received his BS and MS in Mechanical Engineering from The Ohio State University. He received a Ph.D. in Industrial Engineering from Ohio State in 2006. Dr. Wallace has worked actively in a variety of manufacturing industries since 1991 and is currently an Assistant Professor at Youngstown State University in the Department of Mechanical and Industrial Engineering.

Darrell R. Wallace, Ph.D. Assistant Professor Dept. of Mechanical and Industrial Engineering Youngstown State University One University Plaza Youngstown, Ohio 44555 Email: drwallace01@ysu.edu Phone: 330-941-3272
Enhancing Machine Safety Education
Through the Use of Virtual Machinery

Abstract

The responsibility for ensuring that manufacturing equipment complies with regulatory and safety requirements frequently falls to the manufacturing engineer. However, there is evidence to suggest that too many practicing engineers are without suitable training in the interpretation and application of safety codes, particularly with respect to machine guarding. Accident data from the Bureau of Labor Statistics (BLS) and Occupational Safety and Health Administration (OSHA) suggest that many of the most serious machine related injuries could have been prevented by proper guarding. Studies have found that degreed engineers, many of whom have responsibility for machine safety, are either uneducated or poorly educated on the subject of machine guarding and safety standards.

A significant challenge to exploring machine guarding in the classroom is the inability to allow students to safely explore guarding problems in an independent and hands-on environment. First, students are not necessarily qualified to operate such machines. Second, it is not advisable to create a laboratory environment in which students are allowed to operate and test machines that have been made deliberately unsafe (despite such machines being the most interesting from a safety standpoint). This paper suggests a possible approach to code compliance education that enhances classroom learning while providing a virtual reality environment within which to safely explore machines that are improperly guarded.

Demo3D is a three-dimensional modeling software that is marketed for its ability to characterize the performance of packaging and material handling systems. Faculty at Youngstown State University are exploring the possibility of adapting this software for use as a virtual reality environment for studying machine safety. This paper explores the opportunities of employing a physics-based 3-dimensional modeling package in concert with expert systems software to enhance students’ understanding of machine guarding, code compliance, and engineering ethics.

Introduction

The manufacturing production workplace is dominated by machinery. That machinery is responsible for many of the most devastating workplace injuries that occur in the United States. Because of their specialized training, engineers who work in and with the manufacturing community have a particular responsibility to ensure the safety of the workplace, especially with regard to machines and guarding.

A 2006 study focused on the problem of accurately identifying machine hazards so that they could be eliminated. Using mechanical power presses as the test case, the study found that the majority of machine related injuries related to equipment were the result of improper application of existing laws and standards. It also found that many manufacturing professionals – including
degreed engineers – were not properly aware of the laws and standards that apply to machinery of any kind.

To address the underlying causes of the incidents leading to injury, a software package called SafetyNET was developed to assist in the identification of hazards. That software was shown to be very effective at identifying machine hazards. \(^2\) Secondarily, the software seems to offer potential to assist in training manufacturing personnel, including engineers, about the legal requirements and safety standards that apply to manufacturing equipment. The research that was conducted with SafetyNET was focused on mechanical power presses, but the resulting inferences are believed to be broadly applicable to most manufacturing machinery.

The inherent danger of industrial machinery and the risks posed by allowing untrained personnel to work with those machines were identified as major challenges to performing the research in that study. The need to control the safety of the environment required a trained press operator to be an intermediary as the participants studied the press. This limited their ability to freely interact with the machine, adversely affecting both research and educational objectives. This paper explores how the expert system software developed in that study can be used in conjunction with a virtual laboratory environment to facilitate learning.

The problems faced in the SafetyNET study illustrate a broader problem that faces machine safety training throughout both academia and industry. It is evident that engineering students and industry professionals are not receiving adequate training with regard to the requirements of machine guarding and safety. For engineering education to be improved in this area, faculty must recognize the importance of this material as an explicit component of the curriculum. Additionally, for the subject to be taught effectively, schools must be equipped with appropriate resources to safely teach students about machine safety.

Until recently, the latter problem has been the more complex problem to rectify. The use of real-world equipment has been limited by the cost of the equipment and the hazards of allowing students to work with the equipment directly. This paper presents a possible improvement to current machine guarding education and training through the use of virtual equipment. The use of computer based models provides students with unfettered access to dangerously dysfunctional equipment. It also allows access to a wide range of machines and equipment that the university may not physically possess.

This paper illustrates the use of a virtual environment to study hazards associated with a mechanical power press. Mechanical power presses are chosen because they are interesting in several regards:

- Prevalent machine in manufacturing environments
- Relatively simple operation
- Very hazardous if improperly guarded
- Governed by very specific guarding and operational requirements

As a preliminary exercise, the mechanical power press is a well defined problem that is relevant from both teaching and pedagogical research perspectives. The capabilities discussed here are applicable to a wide range of industrial equipment and can be extrapolated reasonably.
Scope of the Problem of Machine Hazards

To justify the importance of machine safety education, it is important to understand the tremendous significance of the problem. Understanding the specific types of injuries that occur, as well as their root causes, can also point to key aspects of training that must be addressed.

The National Safety Council (NSC) estimates that the total cost of occupational injuries in 2002 was $146.6 billion.\(^3\) In manufacturing, an industry that is dominated by machinery, a significant number of the injuries are machine related. As might be expected, the rates of machine related injuries for employees in manufacturing are significantly higher than the national average for all employment. A worker in the manufacturing industry has roughly twice the likelihood of suffering a machine-related injury compared to the average American, Figure 1. Machine-related injuries are usually severe. More than half of all machine-related injuries result in some form of permanent partial disability.\(^4\)

![Bar chart showing lost workday injury and illness cases for machinery as source.](image)

**Figure 1: Comparison of lost workday machine-related injury and illness cases for manufacturing employees compared to all private employees (Source: BLS)**

To study the problem of machine hazards, two primary sources of information were used. First, the Bureau of Labor Statistics (BLS) provided data that described the general population of the American workforce and the magnitude of the problem in that context. Second, detailed narratives of specific accidents were obtained from OSHA. Through a review of these data, it was possible to study the general problem of machine safety and the more specific research focus of mechanical power press safety.

There are few injuries that are more devastating than an amputation. Though manufacturing accounts for less than 15% of U.S. employment, it is responsible for nearly 50% of the amputation injuries, Figure 2. Machine operators suffer more than one-third of all of the amputation injuries, Figure 3. From these two graphs, it may be inferred that machine operators in the manufacturing sector represent a very high percentage of the overall amputations that occur.
Machinery is also a significant source of lethal injuries in the manufacturing sector, Figure 4. The BLS indicates that machines are second only to automobiles as a cause of workplace fatalities.

Figure 2: Nearly 50% of all amputation injuries are attributable to Manufacturing (Source: BLS)

Figure 3: Amputation cases broken out by detailed occupation of the victim (Source: BLS)
Understanding the Underlying Causes of Machine Related Injuries

To better understand the factors that affect machine safety, a narrower scope of study was chosen. Of all of the machines that are commonly utilized in manufacturing, mechanical power presses were identified as particularly significant. This determination was based on several factors:

First, an evaluation of the BLS data indicates that machine operators in the Fabricated Metal Products subdivision of Manufacturing are the most likely to suffer a machine related injury. That industry is dominated by press equipment.

Second, the nature of injuries suffered by press operators tends to be severe. Press operators are among the most likely workers to suffer an amputation injury.

Third, the requirements to safely guard and operate a mechanical power press are thoroughly documented. An entire section of the OSHA code (29CFR1910.217) is specifically devoted to requirements of safeguarding mechanical power presses. Mechanical press safety is also addressed explicitly in ANSI B11.1. In the mid-1990’s the identification of presses as a serious safety risk, particularly for amputations, led to the initiation of a focused OSHA emphasis program on press safety entitled, “CPL 2-1.24, National Emphasis Program on Mechanical Power Presses, 29CFR1910.217.”

To provide better insight into the problem of press injuries, narratives were obtained from the published accident investigation narratives available from OSHA’s website (www.osha.gov). A total of 290 relevant OSHA narratives were reviewed by a team of three engineers with experience with power presses. The narratives were coded according to the following rubric:

- Did the injury occur as a result of contact with the point of operation?
- Was the machine missing any required guards?
Did the machine have a required guard that was functional but had been deliberately circumvented?

Did the machine have a required guard that was dysfunctional and had been subsequently circumvented?

Did the machine have a required guard that was in some way ineffective or improper for the application?

Was there a mechanical malfunction of the machine (excluding safety equipment)?

Was there a malfunction of the guarding or safety equipment?

This rubric was used to evaluate fundamental aspects of the injury event that are critical for establishing whether or not the machine was in compliance with the applicable laws. The law requires that the point of operation be completely guarded; thus, any contact with that hazard in the course of operation is a violation. It is of further interest to determine the origin of the missing guard. A review of the narratives may sometimes suggest whether the hazard had always been unguarded or whether some series of actions or omissions had resulted in a lack of proper guarding. The results of coding the 290 OSHA narratives are summarized in Figure 5.

Most of the injuries (82.1%) occurred at the point of operation. Because of the significant hazards posed by the point of operation, it is subject to very specific guarding requirements. Under the applicable OSHA codes, 29CFR1910.212 and .217, the point of operation is explicitly identified as requiring guarding. Surprisingly, a combined 61.7% of cases lacked a proper point-of-operation guard. Based on the high percentage of cases in which no guard was present, one must conclude that there is some reason that employers are not implementing or enforcing proper guarding on these machines.

Figure 5: Results of analysis of 290 OSHA narratives on press injury incidents
Point of operation hazards must be inaccessible to the operator under all circumstances. OSHA is clear on that point. OSHA is also very clear that the responsibility to ensure proper use of guards falls squarely on the shoulders of the employer. Except in cases where an employee has deliberately (and illegally) circumvented a guard without the employer’s knowledge, it should be physically impossible to suffer a point of operation injury. Such occurrences, therefore, must logically indicate a lack of proper guarding or a malfunction of a safety-critical system.

The accident narratives that were reviewed suggest that most press accidents occur as the result of missing or improperly designed guards. This leads to only two likely conclusions: 1.) the employer is deliberately operating in contradiction of the safety regulations and knowingly creating a hazard, or 2.) the employer is unaware of the hazards or does not know how to comply with the requirements of the code. In assessing the problem, the following observations were made:

- One must operate from the assumption that employers generally do not willfully seek to create hazardous operating conditions.
- Review of the OSHA narratives suggests that most press accidents could be prevented by proper compliance with existing regulations.
- Focused enforcement efforts do not appear to have yielded significant reductions in injuries.

Based on these observations, it was concluded that most press injuries are the result of a failure to properly apply and implement the applicable laws and standards. Overwhelmingly, it was found that it would have been impossible or extremely unlikely that the injury could have occurred if the OSHA codes had been followed.

**Engineering Education and Safe Machine Operation**

The review of OSHA accident summaries found that most of the injuries could have been prevented by compliance with the applicable laws. One apparent explanation for noncompliance is that the individuals who are responsible for the machines may not interpret or apply the laws correctly. Though existing methodologies, such as ANSI B11.TR3, are designed to assist in hazard evaluation, most do not provide guidance as to what constitutes a hazard. Software that is specifically designed to guide the hazard evaluation for a particular machine has been shown to be effective, but the underlying problem of compliance seems to be a lack of adequate understanding of the applicable laws and standards. The apparent lack of understanding of these safety requirements seems to suggest a deficiency in relevant education and training.

The role of the manufacturing engineer in machine safety practices is somewhat unclear. Most manufacturing engineers, from a variety of manufacturing backgrounds (manufacturing, mechanical, industrial, etc.), will have some direct interaction with manufacturing equipment in their professional careers. In many cases, the manufacturing engineer is given some level of responsibility for the safe design, implementation, and operation of machinery. Despite that fact, the amount of attention devoted to machine safety in accredited engineering programs – particularly mechanical engineering programs – remains unclear.
Overwhelmingly, the results of the survey of machine related accidents found that most cases occurred where the machine design and installation did not comply with applicable standards. Many of the engineers who work in manufacturing are mechanical engineers who are expected, under ABET requirements, to have specialized qualifications for machine design:

“The program must demonstrate that graduates have: knowledge of chemistry and calculus-based physics with depth in at least one; the ability to apply advanced mathematics through multivariate calculus and differential equations; familiarity with statistics and linear algebra; the ability to work professionally in both thermal and mechanical systems areas including the design and realization of such systems.”

In discussions on the role of engineering education with respect to machine safety, concerns were raised by other engineering faculty about the wording of the above ABET requirement. At the center of the debate was the meaning of the clause highlighted in bold above. Some argued that “work professionally…including the design and realization” necessarily included the legal requirements and applicable standards for designing such systems. Most, however, argued that a thorough discussion of laws and standards was impractical in an academic setting. Further, they argued, many graduates will not actually work in settings where that information is relevant. Instead, they contended, the clause was meant to speak to a “level of care” and the importance of professionalism.

Clarification was sought from Dr. Daniel Hodge, then Accreditation Director for ABET. In a telephone interview, Dr. Hodge was asked if he could explain his interpretation of what the ABET requirement for mechanical engineering was specifically requiring. His reply was unambiguous:

“My sense of the interpretation is that the emphasis is on the professional design and realization of such systems as contrasted with ethics and the broader question of professionalism. And professional design and realization would involve things like adherence to being aware of codes and applicable codes and standards and their application and so forth which is obviously coupled with ethics, but is a bit different.”

Though there is little doubt that engineering faculty support the notion that all engineering students should be competent in the scientific engineering fundamentals, they are seemingly less rigorous in terms of integrating the use of laws and standards. Based on the ABET requirements for mechanical engineering curricula and Dr. Hodge’s clarification, it seems that laws and standards should, in principal, be given a high priority in mechanical engineering curricula. The importance of this priority is accentuated by the potential consequences observed when machines are operated in noncompliance.

The problem of insufficient attention to workplace safety as a topic of engineering study is not new and has not been limited to education in the Unites States. A 1972 UK Committee on Safety and Health at Work concluded:

“...professional engineering institutions could make their concern with the subject much more explicit by including safety and health as an item in their syllabuses and examinations”
More than 20 years ago, a report from the National Institute for Occupational Safety and Health (NIOSH) declared:

"Engineering students should be made aware of occupational safety and health responsibilities, problems and control techniques as undergraduates; the comprehensive practice of occupational safety and health engineering should be taught at the graduate level."8

Despite apparent support from ABET and a history of observations criticizing the absence of adequate engineering safety training in engineering curricula, evidence suggests that the problem persists. It is apparent that both new engineering graduates and practicing professionals tend to overestimate their familiarity with safety concepts. A survey on engineers and their understanding of safety laws found that half of the survey respondents indicated that they felt their knowledge of design safety was “adequate” or better. Unfortunately, the same survey found that very few had ever attended a class, course, or seminar on the topic.9

A 2006 survey of engineering graduates conducted by this paper’s author found similar results. Among the survey respondents were 31 mechanical engineers who had graduated from a variety of programs. The responses of those mechanical engineering graduates are presented in Table 1. The table indicates that 27 of the 31 respondents indicated having had a course in machine design. However, only 6 respondents indicated having been made aware of laws and standards that govern machine design, and none of the respondents could recall having been taught anything about 29 CFR 1910.212, the federal law that governs the guarding of all machines.

Despite the apparent lack of training on the legal requirements of machine design, more than half (17) of these survey respondents indicated that they had been required to modify or oversee the modification of a machine. These engineering graduates indicated that they were engaged in activities that were consistent with their profession, but that they had not been properly trained to perform. Unfortunately, this finding offers support for the conclusion that machines are being designed and overseen by professionals – including engineers – who lack sufficient knowledge of applicable laws and standards.

It would appear that, at the university level, training on machine safety is inadequate. Also, at the industry level, where an awareness of the importance of machine safety is greater, there are clear weaknesses in the safety training. Though a variety of safety training programs and software have been developed to help identify machine hazards, the problem remains that engineering students, practicing engineers, and industry professionals are not achieving the required level of competence in identifying and correcting machine hazards.

It is clear that one major obstacle to improving safety training is the problem of allowing learners to work directly with hazardous equipment. Hands on training would be ideal, but implicit in the process of training is the process of students making errors. As it pertains to work with industrial machinery, particularly in cases where the machine is unsafely guarded, the hazards are simply too great.
Table 1: Preliminary survey results – mechanical engineers

<table>
<thead>
<tr>
<th>Survey Subset:</th>
<th>Preliminary Survey Results – Mechanical Engineers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Respondents in Subset:</td>
<td>Mechanical Engineers holding undergraduate degrees from American schools</td>
</tr>
<tr>
<td>Universities Represented (Number of Respondents)</td>
<td>31</td>
</tr>
<tr>
<td>Akron University (1), Boston University (1), Clemson (2), Duke (1), Lawrence Technical University (1), Miami of Ohio (4), NJIT (1), North Dakota State (1), Notre Dame (2), Ohio State (9), Purdue (1), Texas Tech (1), Cincinnati (2), Illinois (1), Wisconsin (1), University of New Mexico (1), University of New Haven (1)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question</th>
<th>Yes</th>
<th>No</th>
<th>Don’t Recall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Did you have any courses in your undergraduate curriculum related to the topic of &quot;machine design?&quot;</td>
<td>27</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>If you had a course on machine design</strong>, did that course include discussion of the legal requirements of machine design?</td>
<td>0</td>
<td>26</td>
<td>1</td>
</tr>
<tr>
<td>Did the course include discussion of Title 29, Section 1910.212 of the U.S. Code of Federal Regulations?</td>
<td>0</td>
<td>23</td>
<td>4</td>
</tr>
<tr>
<td>If you had a course on Machine Design, were you made aware of the available national and international standards related to the design and guarding of specific machinery? (e.g. ANSI, ISO, DIN)</td>
<td>6</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Have you ever been asked to design or modify a machine (add guards, change feed mechanism, specify tooling, make modifications, etc.), or oversee the installation of a machine in your professional career?</td>
<td>17</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Virtual Training Environments

The best way to learn about unsafe machines is to work with them. However, there is never a circumstance where it is good to operate an unsafe machine. This is especially true if the operator is unqualified. Yet, the process of hazard identification frequently requires that a machine be operated or closely inspected while in a potentially unsafe condition. Those who conduct safety training must balance the benefits of a realistic training experience against the inherent risks of the task. This problem is common in many different types of safety and industrial hazard training.10

In any setting, the safety of the learners should be of the highest importance. Unfortunately, the act of protecting them from the hazardous condition requires that they either be explicitly made aware of the hazards, or the situation must somehow be mitigated while still providing the appearance of the hazardous condition. In either case, the learner’s interaction with the equipment is tainted by peripheral activities that would not be present in a real-world scenario.
The opportunity to create an autonomous and unencumbered learning experience is compromised.

There are also financial considerations that limit the effectiveness of such training. It is highly unlikely that any company or any university will have the full gamut of relevant machines available for the learners to use for safety training purposes. Instead, classroom concepts can be illustrated on one or two machines, but the opportunities to reconfigure those machines are limited at best.

A solution that has been employed successfully to address similar problems is the use of a computer-generated “virtual” environment. These virtual environments may take many forms and may range in complexity from a static computer rendering of an architectural concept to a fully-immersive 3-dimensional experience. Elements of virtual environments include:

- **Static vs. Dynamic Models** – Environments may be used merely to produce static images (illustrations) of the environment or may be animated.
- **User Perspective** – Some environments may be presented from a fixed point of view (as illustrations in a text, for example), or may be immersive 3-dimensional environments in which the learner may move about freely.
- **Reactive / Interactive Models** – Environments may allow the user to interact with their virtual surroundings, effecting changes in the behavior of the system. For example, users may be able to activate a machine.
- **Haptic Models** – Environments may provide tactile feedback to the user as they interact with the virtual environment.

The use of virtual environments is common in some disciplines. For training purposes, this is especially true in scenarios that require potentially hazardous or costly situations have turned to the use of computer simulations to create “virtual” training environments. Flight simulators are ubiquitous training tools in which both military and commercial pilots are able to hone their skills in emergency situations. Surgeons now have the ability to practice virtual robotic surgery procedures. Also, astronauts are able to simulate payload and docking procedures in virtual environments.

In the most sophisticated of these applications, the ability of these virtual environments to replicate real world experiences is enhanced through coordinated motion (as in flight simulators) and through advanced haptic interfaces. Technology is even emerging that will allow individuals to walk through a simulated terrain, experiencing the changes in grade and walking conditions.

**Virtual Environments for Machine Safety Training**

For purposes of machine hazard identification training, these highly specialized systems are far too expensive and far too limiting. The wide variety of machines and environments that may need to be explored require that the system strike a balance between flexibility and cost. Though simple virtual models have been applied to machine safety, the models have not allowed the user to interact meaningfully with the environment.
For purposes of illustration, CAD or 3D modeling are readily available and very effective at showing static representations of a machine or detailed portions of a machine. For textbook illustrations, this method is most appropriate. If the delivery method is expanded to include computer-based presentation (either in a lecture environment or through online media), the model can be enhanced to show the machine from multiple points of view and may even include animation.

In cases where sequence and timing are important, as with moveable barrier guards, animated models are an effective tool for presenting concepts. This methodology has been adopted by OSHA in their online e-tools training courses (Figure 6). However, the e-tools do not allow the learner to explore the environment on their own.

A variety of technologies exist that allow users to navigate through 3-D environments. Most academic programs will certainly have access to solid modeling software such as Inventor, Solidworks, or Pro/E. Most solid modeling packages also include the ability to generate animations. In some cases, these models may even be exported to cross-platform web-friendly formats such as VRML (Virtual Reality Markup Language).

Though some of the desired capabilities for developing a virtual environment for machine safety training are commonly available within solid modeling software, these tools generally fall short of the minimum capabilities needed to effectively replace the need for real, physical machines. A system that could effectively replace equipment for machine safety training must meet several criteria:

- Users must be able to interact with the machine and environment without risk.
- Users must be able to visually inspect all areas of the model and move about unrestricted.
- Objects within the virtual model should behave according to physical laws. (e.g. Objects that are knocked over should fall.)
- Distances and spatial relationships between model components must be accurate and measurable.
- Dynamic motion within the system must be real-time and timing must be observable / measurable.
- System behavior should be governed by virtual controls and sensors.
- System behavior should be easily programmable using industry-standard programming techniques.

Solid modeling programs are readily available to meet most of the above criteria. Unfortunately, they are not able to address the last two specifications. Those specifications are the key elements that would allow the user to interact with the machine as though it were physically there.
Proposed Solution for Developing a Fully-Functional Virtual Machine

The development and testing of the SafetyNET software uncovered a need for a virtual training environment that met the above criteria. However, a review of available solid modeling software turned up no viable solutions to the problem of incorporating machine control. In 2008, the author became aware of the Demo3D software (http://www.demo3d.com) and approached its makers about an unconventional use for the software package.

Demo3D is an industrial modeling and simulation package that has been specifically designed and marketed for simulating material handling systems. It includes the capability to integrate solid geometries, and industry-standard controls through either connection to an external PLC (Programmable Logic Controller), or through an internal software PLC. It also includes physics based dynamics that mimic inertial and gravitational aspects of a model.

The Demo3D package includes a wide variety of materials handling components built in. Though these are potentially interesting from a safety standpoint, they only reflect a very small portion of the broader range of machines to be considered. Other components may be imported from a variety of solid modeling sources. Options include traditional solid modeling and CAD packages, but also include Google’s freely distributed Sketchup software (http://sketchup.google.com).

For exploring this software as a possible teaching instrument, the Sketchup software was chosen. Though the interface for Sketchup is unconventional and not necessarily appropriate for most engineering applications, the software offers several benefits that make it appealing in this application:

- The basic version of Google Sketchup is free to anyone. The slightly more capable Sketchup Pro is free for university faculty.
- Models generated in Sketchup can be directly imported into Demo3D
- Sketchup has been built on the concept of a “community” of users who share model elements.

The free availability of the software makes it ideal for this application. Models that are built in Sketchup can be freely distributed to students. Those models offer many of the capabilities of commercial solid modeling packages, but at no cost to the institution, faculty, or student. Within that environment, students can observe spatial relationships, take measurements, and even see animated demonstrations of machine elements. (Animations can only be created in the Sketchup Pro version.)

The community library of model elements offers a helpful resource to developers. Common objects (benches, tow motors, etc.) and even some major equipment can be found as freely distributed models online. Those components can be incorporated to create a complete virtual workplace.
Once the model is imported to Demo3D, control features can be added. The motion of various machine components can be constrained and the action of those machine elements can be controlled and coordinated through ladder logic programming in the virtual PLC. Between the two software packages (Sketchup and Demo3D), users are able to freely navigate and interact with virtual equipment in a manner that provides adequate information for the user to conduct most of the tests and inspections required for identification of guarding hazards for machines.

**Proof of Concept – Developing the Virtual Facility**

To illustrate the use of these two software packages for machine safety training, a virtual work cell has been created. This work cell is designed to illustrate some of the merits of the proposed virtual environment in the context of machine hazard training. It will also be used to illustrate the potential use of the software in the broader context of occupational health and safety.

The virtual facility includes a small work cell with a 200-ton part revolution mechanical power press. Material handling equipment passes through the work area and services equipment in adjacent rooms. In the room adjacent to the press is a laser table. Access to that room is protected by electronically interlocked doors. This small facility is shown in Figure 7.

The user can perform a virtual inspection of the facility as though they were walking through the plant. Using the keyboard or mouse, the user can do a basic “walkthrough” as though they were in the real environment. For aspects of a particular machine that may be of interest, the user can zoom in on features for a closer look.

Within both the Demo3D and the Google Sketchup environments, scaled models of operators have been included to give the user a sense of perspective and relative sizes. Aspects of the model that are mechanized or automated in some way have been programmed from within the Demo3D environment (Figure 8).
Proof of Concept – Interacting with the Virtual Environment

Using the virtual facility described above, some of the aspects of a potential student interaction with the virtual environment are explored. The objective of this presentation is not to show a complete hazard analysis of a press installation. Rather, it is intended to illustrate some of the key interactions that are unique to the proposed virtual learning environment in the context of studying machine safety.

Identification of Machine Type and Applicable Codes

A student who is learning about the requirements for machinery would be expected to be familiar with the general guidelines that apply to all machinery. Unless explicitly exempted, U.S. law requires that all machinery comply with 29CFR1910.212, “General Requirements for all Machines.” At the bare minimum, a student studying machine guarding would be expected to know that they must comply with this law. With the text of the CFR in hand, they could explore the machine and verify aspects of compliance or non-compliance.

Additionally, students would likely be expected to know that there may be additional requirements imposed for specific machinery. In this case, the machine of interest is a mechanical power press with a part-revolution clutch. Guarding of this machine is covered by 29CFR1910.217 as well as ANSI B11.1. To illustrate the use of this model, selected requirements of 29CFR191.217 will be discussed.
Figure 9 illustrates a view of the press work area as seen from within Google Sketchup. In this view, the user may move around the press and work area, taking note of conditions or characteristics that may be relevant to the safe operation of the machine. Because there is no risk of injury or damage, even a complete novice can explore the machine freely.

Figure 9: View of the virtual press work area

Engineers who are going to work with or design equipment need to be able to interpret applicable laws so as to be compliant. Similarly, to properly inspect a machine, the user must understand the applicable laws and be able to identify the type of machine they are working with. The legal requirements for guarding a particular machine may change based on its function or classification. This is true for many machines, not just mechanical presses.

An example of machine type-specific laws is the power transmission requirement for full-revolution versus part-revolution clutch machines. Under the code there is a clear distinction between these presses. A student using the software would be expected to recognize the difference in requirements and correctly determine which machine is being studied.
In a traditional classroom approach, the difference would simply be explained and the student may or may not be able to conceptualize the difference. In a supervised laboratory setting, the student could be shown one (or possibly both) variety of presses, but would still be “spoon fed” the information. In the virtual environment, the student can safely be set loose to find the answer themselves. Instructor guidance can ensure a structured learning experience. However, the student can be assured that the operation of the press should provide the information they require. What the student must recognize is that a full-revolution press cannot be stopped mid-stroke; a part revolution clutch press can be stopped at any point in the stroke. Among the many requirements where this distinction would be important is 29CFR1910.217.b(3):

> “Machines using full revolution positive clutches.(i) Machines using full revolution clutches shall incorporate a single-stroke mechanism.(ii) If the single-stroke mechanism is dependent upon spring action, the spring(s) shall be of the compression type, operating on a rod or guided within a hole or tube, and designed to prevent interleaving of the spring coils in event of breakage.”

In the proposed environment, the user would be able to operate the machine from the control pedestal. Within the Demo3D environment, critical controls (such as the palm buttons to operate the press) are tied to designated keys on the computer keyboard. The user would simultaneously press the two keys that correspond to the palm buttons and the press would be activated. If releasing the buttons mid-cycle causes the press to stop, the press is part-revolution. If it continues the full stroke it is likely a full-revolution clutch.

If the user had determined the press to be a full-revolution clutch, through further experimentation and inspection of the press, they would be able to assess whether the two additional requirements above were indeed met.

**Measurements and Timing**

Many safety requirements are measurement and / or time based. Guard openings, for example, are considered safe when they are less than ¼” in width. Some guarding requirements, such as the distance that an operator’s controls must be placed from the point of operation hazard, are calculated based on a combination of distance from the machine and cycle time.

Within the Google Sketchup environment, the user is able to take measurements of any feature. Coupled with the real-time simulation of the machine’s operation, the user is able to observe and record both distances and times needed for determination of compliance.
Assessment of Control Logic

Some safety requirements relate to the control interfaces and algorithms that are used on a machine. Inspection of these aspects of a machine often involves risks from both mechanical and electrical hazards, particularly if the press is faulty in some regard. In this example, the press is operated by a two-hand trip. According to the requirements:

“29CFR1910.217.b.(6) Two-hand trip. (i) A two-hand trip shall have the individual operator’s hand controls protected against unintentional operation and have the individual operator’s hand controls arranged by design and construction and/or separation to require the use of both hands to trip the press and use a control arrangement requiring concurrent operation of the individual operator’s hand controls. (ii) Two-hand trip systems on full revolution clutch machines shall incorporate an antirepeat feature. (iii) If two-hand trip systems are used on multiple operator presses, each operator shall have a separate set of controls.

Examining the press in light of this code requirement, the user should find that the press is, indeed, activated by a two-hand trip. Under the requirements of section (i) above, the hand controls should be spaced such that they cannot be accidentally activated or activated using only one arm. Most commonly, the second part of that requirement is met by adequate spacing between the buttons. Close examination of the control pedestal reveals that the buttons are spaced far enough apart to require separate activation. However, they do not have ring guards to prevent accidental activation (Figure 11).
The exact behavior of the buttons when pressed is also specified by code. For many presses, the type of button function that is specified is called a two-hand no tie-down circuit. Such a circuit requires that both buttons be pressed simultaneously to initiate a cycle and that they must both be released before another cycle can be initiated. This and many other controls requirements for the press can be tested through interaction with the press equipment. If a problem is found or suspected, the user can look at the underlying ladder logic in the PLC. Ladder logic is an industry standard programming language used for nearly all industrial machinery. The ladder logic that controls the two-hand switch for the virtual press is presented in Figure 12.

Figure 12: Ladder logic for PLC control of the virtual press within Demo3D
**Around the Machine**

Requirements for machine safety extend to the area surrounding the machine as well. In the present case, attention should be paid to the spacing between the traffic lane and the operator station. Also, housekeeping around the machine should include the cleanup of any debris or spills (such as those visible in Figure 9). Other requirements such as signage can be inspected from within the environment as well. Figure 13 shows how a user might identify a missing exit door (left) or confirm the presence of a required warning placard (right).

![Figure 13: Inspecting signage in the virtual plant](image)

**Integration with Expert Systems Software**

Because of the complexity of interpreting codes, expert systems software can assist the hazard assessment procedure. The SafetyNET software that was developed for evaluating mechanical power presses has been shown to be very effective at hazard identification. It has also shown that users of the software may gain greater understanding of the codes than students who study the codes without software assistance. The virtual press environment can be used in conjunction with any appropriate methodology for hazard identification. That would include the pen-and-paper procedures specified by ANSI TR3 as well as SafetyNET or any other software assisted assessment tools.

Because the virtual environment allows for the exact duplication of conditions, it provides an interesting platform for conducting research into the relative effectiveness of the various assessment techniques. Users with different backgrounds can serve as test subjects and can identify hazards on identical machines in identical conditions. The relative effectiveness of their hazard assessments can be compared as an evaluation of either the methodology employed or the level of competency achieved.
**Limitations of the Proposed Concept**

The proposed system addresses some of the major needs identified for virtual environments for safety training. Though the system appears viable, there are a number of limitations or opportunities for improvement that have been identified.

*Integration*

The solution proposed here may require the learner to use two or more different pieces of software to achieve all of the capabilities necessary to conduct hazard analyses. It is unclear at this point whether users will be better able to measure distances and determine spatial relationships in Demo3D with the same ease that they can in Google Sketchup. Ideally, the user should have one common interface through which they perform all interactions with the virtual equipment.

Integration of expert systems software to aid in assessment is more complicated; it is also possibly undesirable. In an actual, real-world hazard assessment, the inspector would access their codes and any software they were using separately from the interface to the machine. Similarly, working with the virtual environment, it would be realistic for the user to have their assessment tool operating on a laptop, separate from the computer on which the virtual environment is being generated.

*Cost of Development*

The basic Google Sketchup software is freely available to the public, but the Sketchup Pro version costs $495 for commercial use. Academic users may obtain free licenses for Sketchup Pro. The Demo3D software, however, is substantially more expensive. There are several versions of the Demo3D package available. The most expensive versions, including all of the controls capabilities, may exceed $30k for a commercial development license.

*Cost of Use*

For the learner, the free version of Google Sketchup is adequate. The cost of using the Demo3D platform will depend on the level of interaction the learner needs to have with the model. Depending on the specific application, less expensive run-time versions may be available for training. These typically cost about half of the full version of the software. Developers at Demo3D have been approached about the possibility of creating a feature-limited version of the software that would be specially suited for this application in terms of both capabilities and cost.

*Ethical Considerations*

The use of virtual environments as a teaching tool raises several ethical considerations. First, recognition of the scope of the underlying problem raises concerns about the obligations of practicing engineers with regard to the engineering code of ethics. By extension, evidence that suggests that these engineers are entering the workplace unprepared for a key element of their jobs raises further questions about the responsibility of faculty and engineering programs to include safety training as a more prominent topic of study.
Second, the virtual environment provides a unique learning tool that could be used to discuss some of the very real ethical challenges that face engineers in the workplace. The cost of improperly guarded equipment poses a very real financial and human cost. However, most employers must strike a comfortable balance between level of safety, costs of operation, and productivity. In an ideal world, safety would never be compromised. In reality, safety guidelines are sometimes impractical or impossible to meet to the letter of the law. In some cases it may be argued that the letter of the law actually creates hazards. In such cases, what are the responsibilities of the engineer? What are the options to be considered, and what are their potential consequences? The virtual environment can allow students to develop their own solutions to complex safety questions. The solutions can then be implemented in the virtual environment and the relative merits and limitations of proposed solutions can be discussed.

Conclusions and Future Work

Virtual environments provide a new tool to the academic and industrial communities for offering effective, safe, and economical machine safety training. It is hoped that the identified benefits of software adapted for this purpose will encourage further development to address the limitations of the proposed solution. If software developers can be convinced of the importance of this application, it may be possible to convince them to develop their tools beyond their original scope and into expanded use for safety training.

The capability to easily develop immersive and interactive machinery related environments would be a major innovation in safety education and research. In addition to the clear benefits it offers to safety education, there are research benefits as well. The ability to allow students and test subjects to interact freely with their virtual environment opens up a broad range of opportunities to evaluate the effectiveness of safety training. Not only can students work in a realistic environment, but they may also be assessed in that environment. Based on student performance, the effectiveness of the educational tools may be evaluated and evolved in ways that are not currently possible.

Bibliography

6 Personal phone conversation with Daniel Hodge, 2005


