ABSTRACT. A key issue with the effective use of NDE in the field is adequate training on new and improved technologies. Further, training is expensive and may need to occur at times more convenient for the trainee than the trainer. This paper discusses different concepts for training and transferring inspection capabilities.

INTRODUCTION

Technological advances allowing the development of real-time, physics-based, models of operating environments and equipment; voice recognition and/or cueing for hands-free operation of computers; sensors for position tracking; devices that provide visual, audible, and haptic feedback; and graphics engines that render real-time images of three-dimensional objects and scenes have created tremendous opportunities for innovative and superior approaches for training and performance improvement in the nondestructive evaluation (NDE) of the structural integrity of vessels, piping, tubing and other pressurized equipment. Integrating these technologies in a virtual or mixed reality environment and employing advanced instructional system design techniques provide realistic training approaches in which the students are more engaged and better able to retain the knowledge gained. Additionally, such realistic models could be used to measure the performance of the human-operated systems. This paper will provide several examples of these technologies in NDE applications and suggestions for future developments.

AUTOGRID SYSTEM FOR ULTRASONIC INSPECTIONS

An early example of an NDE application of performance improvement technologies is the AutoGrid system that Southwest Research Institute (SwRI®) developed for the Electric Power Research Institute® (EPRI®) in the late 1990’s to perform wall thinning measurements of complex piping configurations at known, repeatable locations, without the use of mechanized scanning equipment or manually-drawn gridding. The AutoGrid system features a personal computer-based three-dimensional model of the piping that is overlaid by a virtual grid. The traditional inspection technique involves manually marking grid locations on the piping. This labor-intensive approach is very time-consuming and prone to error because it is difficult to replicate the grid from inspection to inspection. The virtual grid in the AutoGrid system allows for more precise and repeatable probe positioning and more rapid inspections. The AutoGrid system is also more flexible for rapidly creating new grid layouts that might be required to further inspect areas where wall thinning may have occurred.

The AutoGrid system utilizes a triangular-mounted array of microphones to locate the position of an ultrasonic inspection probe by measuring the speed of sound from the probe to the microphone array. Probe position information is calculated by the AutoGrid computer.
touching the inspection probe at calibration points on the piping, the AutoGrid software calculates and displays the piping model and generates the virtual grid relative to the microphone array. A probe position tracking interface and display of the piping/grid model facilitates rapid and accurate inspection probe placement with respect to desired inspection points. A heads-up display allows the operator to simultaneously view the object under inspection and the computer visualization display as shown in Figure 1.

**Figure 1. AutoGrid system for ultrasonic inspections**

The AutoGrid system is an example of the use of mixed reality for performance improvement of an NDE application. In mixed reality, visualization of the interaction of physical objects (the piping and the probe) and digital objects (the model of the piping and the virtual grid) are integrated in a real-time simulation environment. Although the AutoGrid application of mixed reality was intended to provide performance improvement of the actual inspection task, other applications of simulation are readily adaptable to NDE training where it is dangerous, expensive, or otherwise difficult to use the actual equipment and physical specimens for training.

**EMBEDDED COMPUTER BASED TRAINING**

For over forty years, SwRI has developed NDE systems for clients around the world. SwRI’s ultrasonic data acquisition systems are used to support pre-service and in-service inspections of reactor pressure vessels and piping systems in both boiling water reactor and pressurized water reactor plants. SwRI now offers these systems with embedded computer based training. Making use of the computers embedded in the inspection system, students are trained on system operation, data analysis, and how to interpret inspection results. It is possible to deliver this training through the World Wide Web. The current generation of SwRI’s Enhanced Data Acquisition System (EDAS™) includes a mode for displaying defects in a mode to simulate scanning for operator training. Additional training features in EDAS include a simulator to generate scanning system position data and ultrasonic instrument data, and a movie system to allow recording and playback of all operator actions and screen results. Future embedded computer based training systems will incorporate more advanced simulation concepts and other techniques for performance support.

**THE NEED FOR NDE SIMULATORS**

The maintenance of aging infrastructure in the power-generation, petrochemical, aerospace, and other industries is a growing concern as the design lifetimes of components are approached or even exceeded. To assure the integrity of these components, new NDE procedures must
there is also a need to train inspectors in order to maintain proficiency. Other inspections are performed routinely in locations where the likelihood of inspecting a component with a detectable flaw is very small; in these cases it might be desirable to provide a method for periodically presenting realistic simulated flaw signals to the inspector in order to maintain a high level of performance. The alternative method of refreshing operators is to intentionally introduce defective components into the inspection process; this approach has the risk of accidental introduction of the defective components into end use.

Although training is best performed with realistic flaws on actual physical specimens, it is often difficult to obtain components with these flaws. Video-based training methods are useful at a high-level; however, they lack hands-on feedback which is such a critical element of many NDE methods. A more capable, versatile and efficient training approach is needed – one that utilizes highly realistic modeling and simulation techniques and technologies.

To be most effective and useful, an NDE simulator should present realistic, virtual flaw signals in a transparent manner to the student using a combination of simulation software and simulated/stimulated inspection equipment. (In mixed reality applications, simulated flaw signals would be injected into actual inspection equipment. In virtual reality applications, the inspection equipment and flaw signals would be simulated.) Flaw types, sizes and locations would be preprogrammed into the simulator without the knowledge of the student. A large number of flaws of different types and sizes can be simulated rapidly and inexpensively in software without the need to generate a corresponding number of flawed physical specimens. Likewise, new fault data gathered from actual field inspections can be quickly incorporated into the simulation to provide the most current training conditions for students. In addition to primary inspection techniques, students could also be trained in general procedures related to instrument setup, probe handling, and scanning methods.

**Eddy-Current Inspection Simulator Prototype**

Under an internal research program, SwRI developed a prototype eddy-current inspection simulator. Operation of the simulator is transparent to the inspector, but realistic, virtual flaw signals (premeasured or generated from a model) are presented at preprogrammed locations as the inspection probe is moved over an actual test piece. This provides the equivalent of an inspection without the need for actual flaws. The operator uses the same probes and instrumentation that are used in a normal inspection. The simulator is connected between the probe and instrument so that flaw responses are injected into the instrument, and the operator sees the response on the instrument display. The probe and instrument remain “live” so that the interaction between the probe and test piece remain active as well. The simulator tracks probe position so that flaw responses are injected at the proper location on the test piece. The simulator is shown in Figure 2.
This innovative simulator approach that utilizes a combination of actual and virtual flaws and equipment provides several potential opportunities for NDE performance improvements.

**NDE training** – although training is best performed with realistic flaws, it is often difficult to obtain components with these flaws. The eddy-current inspection simulator prototype allows for training with either actual or simulated flaws.

**Maintaining the proficiency of inspectors** – some inspections are performed routinely in locations where the likelihood of inspecting a component with a detectable flaw is very small. In these cases, the inspectors can either lose proficiency or become mentally conditioned to not expect flaws, so a flaw response could be easily overlooked. The simulator provides a method to periodically present flaw signals to the inspector so that a high-level of proficiency is maintained.

**Ensuring scan coverage for existing inspections** – some inspections are performed using hand scanning, which relies on the inspector’s skill to ensure that the probe is scanned over the correct area. The simulator monitors probe position, orientation, and liftoff to ensure scan coverage is maintained.

**Determining Probability-of-Detection (POD) for new NDE procedures** – in some inspection regimes, when a need for a new NDE procedure is identified, it must be demonstrated that the developed procedure meets inspection requirements. This is often accomplished through a POD study involving the manufacture of many test specimens, conducting blind tests with multiple inspectors, and analyzing the results. The most time-consuming and expensive part of this process is usually the development of specimens containing precisely defined realistic defects. Providing an appropriate size range of such defects is a difficult art, and the results cannot be reliably predicted. The simulator provides a method for rapidly and reliably producing a wide variety of sizes and types of flaws.

**BORESCOPE INSPECTION SIMULATOR**

Originally developed by SwRI for a major jet engine manufacturer, the Borescope Simulation Training Device (BSTD) utilizes a high-fidelity 3D model of a turbine engine and an intuitive user interface to enable a student to virtually inspect an engine, both externally and internally. The BSTD simulates a turbine with normal wear (i.e., 3,000 hours of operation) and includes a variety of instructor selectable blade and rotor defects as shown in Figure 3.

![Figure 3. Borescope inspection simulator](image)

An engine model is generated from computer-aided drawing files of the actual manufacturing data. Textures derived from photographs of actual turbine components are
rotation of the inlet fan and the compressor rotor to support two critical inspection scenarios: (1) an exterior visual inspection of the inlet fan blades, and (2) an interior borescope inspection of the compressor fan blades.

This application of virtual reality to common inspection tasks has several innovative features. The student uses a joystick to “fly” around the virtual turbine engine model to inspect for external defects. Various tools are selected from a dropdown menu. The student can then rotate the inlet fan and turn on a virtual flashlight to perform an external inspection. The student clicks on access ports to insert a simulated borescope to perform internal inspections.

The borescope view simulates either rigid or flexible probes with a selection of viewing-angle tips. The borescope video image is displayed in a pop-up window with lighting and measurement controls. After inserting the probe, the student manipulates the borescope view using the joystick controls. Another pop-up menu allows the student to rotate the compressor rotor to search for defects and extract the probe.

**WEARABLE WORKSPACE CONCEPT**

There are a variety of inspection, maintenance, and repair environments where it is difficult to access and effectively use information contained in traditional paper documents or displayed on computer screens. To address this problem, SwRI has developed a concept for a wearable workspace. This is a low-cost, portable, hands-free system for accessing electronic technical manuals, drawings, troubleshooting procedures, just-in-time training, and performance support tutorials. These job aids are invoked through various voice commands and/or head motions that are then presented on a head-mounted monocular display as shown in Figure 4.

![Figure 4. Wearable workspace concept](image)

Electronic technical manuals offer many advantages over traditional paper-based documents: they take up little or no physical space, can be wirelessly downloaded and updated, can be stored in large numbers on a single platform, and can be easily shared by a large number of users. While the use of electronic technical manuals is rapidly increasing, the benefits are limited by the need to access the information on a computer platform that takes the user away from the task at hand. New technologies such as ultra-mobile personal computers and lightweight head-mounted displays provide a portable means for presenting electronic information. SwRI has developed a wearable workspace prototype using commercial off-the-shelf components at minimal cost. SwRI is investigating ways to further reduce the size and cost of the wearable workspace. One concept under study is to host the wearable workspace software in popular palmtop tools such as the Apple iPhone or Windows Mobile devices.

It is difficult to develop methods to easily and reliably interact with electronic information while completing manual tasks. A key innovation of the wearable workspace is the incorporation of a three-degree-of-freedom head tracking device in addition to the microphone.
interacting with the electronic information through a combination of voice commands and head motions. Test results show that this combination of inputs is more robust than voice recognition alone in noisy environments.

**UBQUITOUS LEARNING MODEL**

The preceding examples of the many approaches that are available for training and performance improvement lead to the question of how to select the appropriate blend of technologies and methodologies for specific applications? A conceptual model for making such selections considers the skill level of the student and the underlying knowledge about the task. The skill of the student ranges from novice to expert. The underlying knowledge about the task ranges from known to unknown. The ubiquitous learning model describes the optimal interaction between three key elements to support moving the student from novice to expert on a variety of tasks. These elements are the social sphere, the delivery platform, and the learning approach.

The social sphere considers the importance of collaboration and interaction in learning and performing the task. Some tasks are simple and require little or no collaboration or interaction to master. Other tasks are complex and require teamwork to complete. The training approach should match the relative degree of collaboration and interaction that is required for the task. Higher degrees of collaboration and interaction require better connectivity between the team members. Digital technologies facilitate these high degrees of connectivity. There are many ways that students can connect digitally and these different tools support learning in different ways. The simplest approaches today include internet searches, wiki’s, and blogging. There are more sophisticated programs like twitter and chat rooms, and many different forums for sharing information. Even more sophisticated are collaborative knowledge bases.

The delivery platform considers how instruction is actually delivered to the student and whether a single or blended approach most effectively supports learning. These approaches range from traditional classroom instruction and on-the-job training on the “low tech” end of the spectrum. New technologies are making possible other methods of delivery such as web-based training, gaming, virtual worlds, mobile learning, and wearable computers.

The learning approach considers the various instructional theories ranging from behaviorist to constructivist and which approaches are best suited to the skill level of the student and the underlying knowledge about the task. Behaviorist theories focus on basic facts, fundamental skills, and a linear step-by-step approach with immediate feedback. Constructivist theories focus on higher-level, problem solving tasks where the student does more discovery learning.

Figure 5 illustrates an example of the ubiquitous learning model applied to several training tasks associated with the inspection of piping using magnetostrictive sensor (MsS)- based guided wave technology. The x-axis represents the skill level of the student and the y-axis represents the underlying knowledge about the task. The four quadrants of the illustration represent the following tasks:
Bonding an MsS sensor to a clean pipe (lower left quadrant) – this represents the appropriate combination of elements for training a novice to perform a relatively simple, well known task. The preferred learning approach for this task would be highly behaviorist (step-by-step instruction). The application requires little collaboration or interaction, which could be accomplished face-to-face with an instructor or by relatively simple internet searches or blogs. The best delivery platform would be classroom training, self-paced instruction or even a live webinar.

Bonding an MsS sensor to a clean pipe underwater in a controlled environment such as a laboratory (upper left quadrant) – this represents the appropriate combination of elements for training a novice to perform a more difficult task. The learning approach for this task would include a combination of behaviorist and constructivist (practice) activities. This task would benefit from a greater degree of interaction, such as chat rooms or twitter. An appropriate delivery platform would be web-based training, which allows the combination of instruction and practice.

Bonding an MsS sensor to a corroded pipe with insulation (lower right quadrant) – this represents the appropriate combination of elements for training an expert to perform a well known task for this higher skill level. The learning approach for this task would be a combination of behaviorist and constructivist activities. More sophisticated methods for interacting with other experts, such as online forums, blogs, and chats would facilitate learning. The best way to deliver the instruction would be via simulation.

Bonding an MsS sensor to a corroded pipe underwater in a field environment (upper right quadrant) – this represents the appropriate combination of elements for training an expert to perform an unknown task, such as might be encountered in a field environment when just-in-time delivery of training and performance improvement support is needed. This task would require a highly constructivist approach. Much greater interaction with other experts would be needed. Collaborative knowledge bases or collaborative groupware like Skype, NetMeeting, WebEx, iPeerAdvisory and others would be useful to harness the power of networks of people and relationships. Group members can interact in real time or asynchronously even though they are not at the same physical location. Technologies that are useful for distributing collaborative intelligence and to facilitate group problem solving include synchronous conferencing technologies like instant messaging, online chat, and shared white boards. Asynchronous messaging like electronic mail, threaded, moderated discussion forums, and web logs are also useful.

EXPERT KNOWLEDGE TRANSFORMATION

One of the biggest problems facing most industries that rely on highly trained and experienced staff members is how to avoid losing their knowledge when the staff members leave the organization. Many experts in the NDE field are retiring, and when they retire tremendous knowledge leaves with them. As a result, companies are interested in knowledge management, which are organizational practices that make expert knowledge available throughout the organization. Knowledge refers to the expertise and skills that a person acquires from education, training, and experience through perception, learning, and reasoning. Knowledge consists of two major forms: explicit knowledge and tacit knowledge. Explicit knowledge refers to documented knowledge that individuals typically acquire through education, training, and self-study. Tacit knowledge refers to the undocumented knowledge that individuals acquire through experience. Tacit knowledge is valuable because it includes the “lessons learned” or “tricks of the trade” that are not easily documented, but are vital in translating theory to practice when moving from the classroom to a field environment, and is what distinguishes novices from experts. Tacit knowledge is not easily shared. It often consists of habits and other patterns of behavior that people do not even recognize in themselves. Therefore in the field of knowledge management, tacit knowledge refers to knowledge that is only known by an individual and that is difficult to communicate to the rest of the organization.
or articulation. SwRI developed an Expert Knowledge Transformation (EKT) model and process to capture an expert’s tacit knowledge, codify it, preserve it, and communicate it to novices through training and performance support systems. A key element of this process is a validation step, which distinguishes it from typical communities of practice and wiki’s where the truth and value of the information can be suspect. The SwRI EKT model consists of the following elements:

**Conduct an organizational value analysis and prioritize the information** – a tailored organizational value analysis is performed to determine what knowledge is of value, what knowledge is in danger of being lost, and what the capture priority should be. The common criteria for this analysis are:
- imminence of attrition of the experts,
- depth of expert staffing,
- frequency of tasks requiring expert knowledge, and
- steepness of learning curve moving from novice to expert.

**Capture tacit knowledge from experts in digital form** – tacit knowledge is elicited from experts through personal interviews in various digital formats, including audio and video. Experts are asked to reflect upon their individual experiences. Through a series of questions tacit knowledge is obtained from the experts.

**Code the knowledge objects to facilitate searching, tracking, and maintenance** – each knowledge object that is captured is individually coded, tagged, and indexed. The resulting information can be used for keyword searches, browsing, navigation, retrieval, and object maintenance.

**Share the objects via searches and just-in-time integration** – the objects are stored in a repository for easy searching and can provide just in time training on demand.

**Maintain a knowledge-sharing culture** – it is important to consistently foster and support a knowledge sharing culture within the organization.

**CONCLUSIONS**

Recent developments in training, simulation, and performance improvement technologies are just beginning to be applied to NDE. There is a great deal of potential benefit applicable to NDE areas by leveraging this technology. Benefits include reduced cost of performance characterization, reduced training costs and inspection proficiency maintenance, and expert knowledge transfer.