Digging Into Simulation

An SwRI-developed simulator helps train excavator operators safely and effectively

Simulated operations of excavation machinery include positioning of loaded dirt into the bed of a truck.

By J. Brian Fisher

Southwest Research Institute (SwRI) engineers have developed an effective and affordable alternative for training heavy-construction equipment operators through modeling and simulation.

In large part, construction equipment operators are trained using actual machinery. The cost-effectiveness of this practice is undermined by direct and indirect costs, such as rental fees, fuel, wear and tear, instructor salary and opportunity costs incurred while the equipment is pulled away from profitable work on the jobsite to support training. In addition, using actual equipment for training increases risks of personal injury or property damage and limits the opportunity for instructional feedback.

To address these issues, a team of engineers from Southwest Research Institute (SwRI) developed the Excavator Operator Training Simulator (EOTS) in cooperation with a major manufacturer of construction equipment. This system, which operates on a personal computer, provides several advantages over traditional training approaches.

Instructors can use it to teach skills ranging from simple tasks to complex procedures. Trainees practice in a risk-free environment, without the potential for equipment damage or personal injury. This portable system provides highly accessible training that is not restricted by real-world limitations such as inclement weather and equipment availability. Finally, the system provides detailed performance measurement, with immediate and meaningful instructional feedback to students.

While simulation-based training has been used for many years in high-end military and commercial applications, the costs associated with such training limited its use to applications such as flight simulators. Only recently has this approach become cost-effective for training on a broader range of equipment. However, affordability is not the most important quality associated with simulator applications. Without a sound instructional approach, using a simulator to teach heavy-equipment operator skills would be ineffective. By combining the Institute's extensive experience in modeling and simulation with the manufacturer's expertise in construction equipment and associated training methods, the SwRI team developed a system that provides a meaningful training experience, motivates the trainee and supports learning by accurately simulating the working environment.

Providing meaningful training

Some training simulators simply model system behavior and allow the trainee to perform fairly arbitrary or mundane activities. In contrast, the EOTS focuses on training in the context of real-world tasks. It provides numerous lessons centered on key situations the trainee will face day after day on the job, such as maneuvering and positioning the excavator, digging trenches straight and level, loading trucks efficiently, moving and placing loads such as trench boxes and pipe, and loading the excavator onto a trailer for transport.

Each lesson is designed to familiarize trainees with the controls and associated equipment responses so they learn the proper skills and techniques before they use a piece of equipment for the first time.

While proper technique is important, safe operation is even more so. It must be learned and practiced before an operator can work effectively on a real jobsite. Each EOTS training lesson includes potential safety hazards that trainees must recognize, and situations to which they must respond properly in order to complete the lesson. Simulated safety hazards include operations near power lines, open trenches, other equipment, facilities and personnel. In addition, trainees must learn to maintain proper load limits to avoid tipping. To build safety habits, the EOTS provides a practice mode in which trainees receive real-time warnings as they encounter potential safety hazards during a lesson. This trains the operator to recognize potential dangers and correct his or her behavior in time to avoid unsafe conditions. The trainee is later tested, operating the simulator in an assessment mode where no warnings are given. This forces the student to recognize hazards, just as on a real jobsite.

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Motivating the trainee

Truly effective training requires that the trainee be motivated to complete the learning objectives. The SwRI team implemented a unique scoring approach that provides a competitive environment where performance is measured in terms of financial success and ranked against other trainees. In each lesson, profits are calculated based on a comparison of the trainee's productivity against the labor and equipment costs incurred. In addition to being productive, the trainee must complete the lesson while avoiding actions that would damage the equipment or the jobsite. Careless behavior, such as slamming the bucket or hitting other equipment, reduces a trainee's profits by deducting costs associated with equipment damage.

Safety also plays a key role in the scoring. The same zero-tolerance approach to unsafe actions on the jobsite applies in the EOTS simulator. A trainee's action that leads to a safety violation results in a no-score, and the student must repeat the lesson. This scoring approach not only motivates the trainee by encouraging competition, but also provides a constant reminder that performance affects the bottom line and that safety is the top priority.

Imagery generated as part of the SwRI-developed training software is designed to be as faithful as possible to actual excavating equipment, shown here, in order to aid operators' transition following completion of their training.

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Trenching activity is simulated using SwRI-developed software that can train operators to excavate a trench, hoist and position a retaining structure inside it, and then operate the shovel within the workspace of the retaining structure, all without risk to personal safety.

Simulating the jobsite environment

Providing realistic training in a virtual construction environment presents numerous technical challenges. Sophisticated techniques must be applied to model the physical and visual characteristics of the excavator and its interaction with the jobsite to support the broad range of activities included in the EOTS lessons. The coupled motion of the excavator and its various articulated parts must be modeled accurately and efficiently to support effective training. Operator control actions must produce accurate movements of the articulated parts and maneuver the excavator in a manner consistent with actual equipment performance. In addition, the dynamics model must accurately simulate the equipment response associated with stalling the bucket while digging, moving heavy loads such as pipe or trench boxes, tipping the excavator when load limits are exceeded, and detecting collisions to determine when equipment has been damaged. While these types of models have been developed for many types of simulators in the past, implementing them for a complex construction environment in a manner that supports real-time performance on widely available, consumer-level PCs requires careful implementation and optimization.

Dirt modeling

The most challenging aspect of building a virtual construction environment was to develop realistic physical and visual models of the interaction of the excavator bucket with dirt. By combining kinematic models with surface and volume modeling and rendering techniques, the SwRI team developed a sophisticated dirt simulation to support numerous training features, including loading of the bucket; dirt flow, piling and retention; and an accurate generation and realistic depiction of trenches.

Bucket loading algorithms are based on the volume swept by the bucket, and they compensate for stalling conditions associated with dirt properties as well as the bucket's attitude and the speed and direction of motion. Methods for determining how dirt is retained in the bucket, and how it flows from the bucket and accumulates on the ground or in other vehicles, are based on the angle of repose, the bucket's motion and the dirt's properties. Additional techniques were implemented to generate and display realistic trenches, including a combination of cut surfaces and loose dirt to provide visual cues that help the trainee ascertain depth.

The visual depiction of bucket/dirt interactions is generated using a pre-tessellated surface with configurable grid spacing that divides the training area into a number of polygonal faces. This grid is deformed in real time as necessary to display the movement of dirt in response to trainees' actions. By allowing the grid to be configurable, users are able to maximize the display fidelity based on the capabilities of their PC graphics card.

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Military application of the excavator operation simulator allows trainees at multiple stations to work independently on different phases of excavation while being supervised by a single trainer.

Various textures are applied to the dirt to allow trainees to easily distinguish between various static and dynamic states of the dirt, such as undisturbed surfaces, nearly vertical cut surfaces, and/or loose surfaces. Small amounts of dirt falling from the bucket or passing around the edges of the blade are modeled with particle effects subject to gravity and minimal collision detection. Larger volumes of dirt moving out of the bucket and onto the ground, or into another piece of equipment, or larger volumes of soil being forced around or over a blade are modeled as a procedural solid with animated, dynamic or procedural textures to enhance the appearance of motion.

Auditory and visual cues

To provide a cost-effective solution, motion is not included in the EOTS. Without motion, appropriate visual and sound cues assume greater importance in providing primary feedback to the trainee. Visual cues that allow the trainee to sense motion and depth are critical to operating equipment in this type of environment. The addition of detailed visual models, real-time simulated shadows, texturing, and shading help to provide these cues. Sounds also provide valuable cues to the trainee to help assess the performance of the equipment. The EOTS includes numerous sounds to reinforce visual cues. These sounds provide feedback that helps a trainee determine how quickly the excavator and its parts are moving, or when the hydraulic system is laboring to indicate an impending blade-stalling condition.

The use of realistic controls that respond like those in the equipment also plays a key role in providing an effective training environment. While the EOTS is capable of supporting gaming joysticks, most customers prefer the optional “replica” controls that provide a more accurate feel. These controls, which include a set of joysticks and foot pedals, were constructed from actual excavator components and provide a range of motion, feel and equipment response which closely matches that of the actual equipment.

Conclusion

SwRI and its collaborators have applied advanced simulation techniques and a sound instructional approach to create a cost-effective method for training excavator operators. Numerous systems have been delivered to various clients in the United States and abroad, including commercial construction companies, equipment dealers, operator unions and training organizations. These systems have proven themselves as a valued resource not only for training, but also for supporting business development, recruiting activities and the screening of potential new employees as a tool to determine skill level.

SwRI also has produced a customized version for the U.S. Army training school at Fort Leonard Wood, Missouri. Customized hardware and software were delivered for 30 complete simulators as a precursor to training on actual equipment and to supplement training during inclement weather.

The EOTS is the first in a line of heavy equipment training simulators planned for release. SwRI and its collaborators are developing additional training simulators for a four-wheel loader and a motor-grader, and others are in the planning stages. Each subsequent simulator will leverage and extend the capabilities of the architecture and approach developed for the EOTS. This proven approach will allow these systems to continue to reduce training costs and risks while providing a highly accessible, cost-effective training basis for years to come. v

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