

Applying Low-Cost Simulation to Training of Construction Equipment Operators

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ABSTRACT

In large part, construction equipment operator training is conducted using actual equipment. Personnel costs for operators and instructors; equipment costs including fuel, maintenance, and wear and tear; and indirect costs associated with removing equipment from productive work limit the cost effectiveness of this approach. Furthermore, the use of actual equipment increases risk and limits the opportunity for instructional feedback.

While simulators have been used to reduce the need for actual equipment in training for many types of military systems, they have not, as yet, been used in large part to support training for construction equipment. The Construction Equipment Virtual Trainer Hydraulic Excavator (CEVT HyEx) represents the U.S. Army's initial use of simulation to support training of construction equipment operators. This system provides cost-effective training in a risk-free, highly accessible environment for personnel with little or no experience in operating excavators. The simulator models the form, fit and function of the Hydraulic Excavator Model 230 LCR controls and provides instruction in basic machine operation and skills through a training curriculum progressing from control orientation through complex application tasks. The CEVT HyEx incorporates ten interactive training lessons which focus on operator technique and safety; and, are designed to increase the operator's awareness and confidence, provide the ability to train in inclement weather and reduce equipment damage and soldier injuries. Detailed performance measurement capabilities provide immediate and meaningful feedback to operators and provide a mechanism for assessing and tracking performance through the training curriculum.

This paper will describe how the capabilities of the simulator are being used to support the Army's increasing training needs at the Army Engineer School at Fort Leonard Wood, MO. We will discuss how the simulator supports a new crawl-walk-run training approach being implemented by the Army, and will describe future plans for incorporating additional simulators.

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INTRODUCTION

Each year the military completes hundreds of construction projects. Tons of earth and building materials must be moved to build airfields, roads, dams, and buildings. Highly trained equipment operators are needed to efficiently and safely perform these tasks using numerous types of equipment, including excavators, bulldozers, loaders, cranes, graders, and scrapers.

The U.S. Army Engineer School at Fort Leonard Wood, MO prepares military construction equipment operators for active duty through a combination of classroom and hands-on training. Inclement weather, direct and indirect costs (such as rental fees, fuel, wear and tear, lost opportunity costs, etc.), equipment availability, and instructor availability limit training opportunities. In addition, using actual equipment for training increases personnel risks and the potential for property damage, and limits the opportunity for immediate instructional feedback.

Currently, construction equipment operators make up one of the highest demanded units in the Army's theatre of operations. As Army operations continue to change, the demand for training increases. As student throughput needs continue to increase and training costs continue to rise, it is becoming apparent that an alternative is needed to supplement and complement hands-on training. Failure to meet these training demands will impact the Army's strategic and operational goals.

While simulation-based training has been used for many years, the associated costs have somewhat limited its use. Only recently has simulation become cost-effective enough to be considered for a broad range of training, such as the operation of construction equipment. However, affordability is not the only consideration. Without a sound instructional approach, using a simulator to teach heavy-equipment operator skills would be ineffective. Effective training requires an approach that provides

a meaningful training experience, motivates the student through immediate and appropriate instructional cues and feedback, and supports learning by accurately modeling the working environment.



Figure 1: CEVT HyEx Simulator

In response to this need, the U.S. Army initiated the Construction Equipment Virtual Trainer (CEVT) program to incorporate simulation into current training methods at Fort Leonard Wood. The initial system fielded for this program was the Level 1 CEVT Hydraulic Excavator (HyEx) simulator (see Figure 1).

TRAINING/SIMULATION REQUIREMENTS

Military construction equipment operators must master a broad range of skills in complex environments on a variety of equipment. For a new operator, operating the complex controls on a new piece of equipment for the first time can be both intimidating and potentially hazardous. To minimize the risk of damage or personal injury, operators must first develop a solid understanding of basic earth moving techniques and knowledge of potential safety hazards prior to operating a piece of equipment on

the job. Therein lays the issue. Even these initial skills are most often trained using actual equipment.

While simulation is specifically designed to address situations such as this, there are several challenges to modeling a construction environment for operator training. To effectively train construction equipment operators, a simulator must be capable of providing:

- Accurate visual and physical representations of terrain/equipment interactions
- Realistic simulated equipment performance in response to student actions
- Meaningful instructional cues and feedback consistent with the operator's performance
- An environment in which training can be performed in the context of real-world tasks

Due to large class sizes and the limited space available at Fort Leonard Wood, the CEVT HyEx simulator also needed to use low cost components in compact systems which require minimal instructor intervention.

SYSTEM OVERVIEW

As outlined below, the CEVT HyEx simulator meets these needs using a combination of commercial off-the-shelf (COTS) equipment, specialized controls, and custom software. This system provides cost-effective training in a risk-free, highly accessible environment for personnel with little or no experience in operating excavators.



Figure 2: CEVT HyEx at Fort Leonard Wood

Hardware

To meet student throughput levels, it was determined that a total of 30 systems would be required.

Available space was limited, so the simulator footprint was a major consideration (see Figure 2). To accommodate this, the CEVT HyEx simulator provides only the major controls necessary for initial training in a simple, compact aluminum framework (see Figure 3). Controls include a hydraulics shut-off lever, joysticks, and foot pedals constructed from actual excavator components and modified to provide a Universal Serial Bus (USB) interface to a personal computer (PC). These controls simulate the form, fit, and function of the actual controls allowing students to virtually practice controlling and maneuvering the simulated excavator in much the same way as the actual equipment.

Each CEVT HyEx simulator uses a single COTS PC with the following basic specifications:

- Operating system: Window XP Professional
- CPU: Intel Xeon CPU, 2.0 GHz
- Memory: 1 GB of RAM (2 GB recommended)
- Video card: NVIDIA 7800 series or better, 256MB video RAM (512 MB recommended)
- Disk space: 1 GB of free disk space
- Display: 46 inch flat panel monitor



Figure 3: CEVT HyEx Controls

The simulator PCs are attached to a network along with a dedicated workstation which allows an instructor to set up student accounts and to monitor student scores. A simple user interface allows an instructor to quickly review scores at multiple levels to monitor how students are progressing over time. As illustrated in Figure 4, scores can be viewed for entire classes, ranked by overall scores or by individual tasks to determine which students need additional help in specific areas. This interface also allows instructors to access detailed lesson reports which provide more in-depth information on how the students perform in each task. By providing quick access to this information,

the burden on the instructors is reduced allowing them to more efficiently and objectively track students.

All Tasks		
Jobsite/Average Score	Operator	Overall Score
Class 1 May 2009 82	Joe Webster	94
	Ryan Logan	92
	Chad Zalkin	87
	Amanda Jones	71
	L. Cruz	64
Jobsite/Average Score	Operator	Overall Score
Class 2 June 2009 86	A. Sanchez	97
	Jose Pena	89
	J. Goodnev	87
	James Smith	86
	Jerry Jones	82
Jobsite/Average Score	Operator	Overall Score
Class 3 July 2009 84	B. Jenner	95
	R. King	95
	Les Hughes	81
	Ken Huffman	80
	Dave Ross	70

Figure 4: Instructor Station Score Sheet

Software

The CEVT HyEx simulator software models the physical, visual, and aural characteristics of the hydraulic excavator and its interaction with the jobsite.

Equipment Modeling

The coupled motion of the excavator and its various articulated parts are modeled to ensure operator control actions articulate and/or maneuver the excavator consistent with actual equipment performance. Equipment models also include effects associated with bucket stalling while digging, moving heavy loads such as pipe or trench boxes, and tipping the excavator when load limits are exceeded.

Dirt Modeling

The most challenging aspect of the CEVT HyEx simulation software was to provide realistic physical and visual models of the interaction of the excavator bucket with simulated dirt. A combination of kinematic models and surface/volume modeling and rendering techniques are used to simulate various behaviors associated with bucket loading, dirt flow, piling and retention, and the generation and depiction of trenches.

Bucket loading algorithms are based on the volume swept by the bucket, and compensate for stalling conditions associated with dirt properties and the bucket's attitude, speed, and direction of motion. Dirt retention and flow from the bucket and accumulation on the ground or in other vehicles are modeled based on angle of repose, bucket motion and dirt properties. Trench models include a combination of cut surfaces

and loose dirt and include visual cues that help the student ascertain depth.

Visual depictions of bucket/dirt interactions are 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 a student's actions. Various textures are applied to the dirt to allow students to easily distinguish between various states such as undisturbed surfaces, nearly vertical cut surfaces, and/or loose surfaces. Particle effects and procedural solids with animated, dynamic or procedural textures are used to depict various types of dirt movement including dirt falling out of the bucket and onto the ground, or into another piece of equipment, or volumes of soil being forced around or over a blade.

Visual and Sound Cues

Visual cues that allow an operator to correctly and efficiently manipulate buckets and/or blades to support earth moving activities are critical to operating construction equipment. In the absence of a motion platform, simulated visual and sound cues assume an even greater importance as the primary means for conveying depth perception and the sense of motion. Detailed visual models, real-time simulated shadows, texturing, and shading help to provide these cues in the CEVT HyEx (see Figure 5). In some cases, artificial visual cues are also included, such as tipping gauges, truck fill gauges, and layered coloring inside a trench to indicate depth, to further compensate for the lack of motion and depth.



Figure 5: Shadows, trench coloring and gauges enhance depth perception

Sounds also provide valuable cues to the student to help assess the current state and performance of the equipment. Numerous sounds reinforce visual cues and provide feedback. This helps a student determine how quickly the excavator and its parts are moving or when the hydraulic system is laboring to indicate an impending blade-stalling condition.

USE IN TRAINING

The ability to accurately simulate a piece of equipment alone does not make for an effective training system. The simulator must be based on a sound instructional approach and must be used in the appropriate way to support effective training. At Fort Leonard Wood, the CEVT HyEx simulator is used to facilitate a crawl - walk - run approach designed to minimize costs and maximize student throughput. This three-phase approach uses a combination of classroom instruction, computer-based training (CBT), Level 1 simulators and actual equipment.

During the crawl phase, students learn the fundamentals of equipment operation through a series of classroom lessons and CBT. The Level 1 CEVT HyEx then provides a bridge between classroom instruction and hands-on training by allowing students to virtually apply the knowledge they have attained, learn and practice operating techniques, and assess their basic capabilities.

In the walk phase, students will further use the simulator by completing multiple scenarios which mimic real-world tasks and having their skills assessed. From there, students will use mini-excavators to further hone their knowledge and basic skills. The use of mini-excavators allows students to practice the same basic operating techniques they learned on the simulator and will use on the full-size excavator. This reduces operating costs and the potential for damage and serves to increase the students' confidence on a less intimidating machine.

Finally, students complete their training in the run phase by working with actual excavators. Equipment owning and operating costs, fuel costs, equipment maintenance, and the need for sufficient land to operate make this the most expensive portion of the training. By leveraging the knowledge, skills, and confidence gained during the crawl and walk phases, students are much better prepared by the time they get to this phase and are able to learn more cost-effectively and efficiently.

Training Lessons

To help facilitate the crawl-walk-run approach, training lessons in the CEVT HyEx simulator directly support the types of activities students will be exposed to throughout the hands-on training and while on the job. By emphasizing a consistent set of objectives, the simulator supports continuity in training experiences which facilitates a seamless transition through the phases.

The CEVT HyEx incorporates ten interactive training lessons providing instruction in basic machine operation and skills through a curriculum progressing from basic control orientation through complex application tasks. These lessons include the following:

- Simulator Familiarization
- Operator Controls Overview
- Placement for Trenching
- End of Day Parking
- Loading Trucks From a Bench
- Digging a Level Trench
- Setting a Trench Box
- Placing Pipe
- Loading onto a Trailer
- Loading Objects with the Thumb

Focus on Basic Technique

The emphasis for each lesson is on increasing the operator's awareness and confidence by first getting the students familiar with the controls and then having them learn to develop and practice efficient operating techniques that will ultimately make them more productive on the job. In each case, students are scored based on their ability to achieve various objectives. These objectives vary from lesson to lesson, but generally measure how quickly students complete a lesson, how efficiently they move material without spilling, and/or how well they maintain grade in a trench, etc.

In addition to teaching students to be productive, the instructors must ensure students understand how to avoid actions that would damage the equipment or the jobsite. The simulator reinforces this by tracking careless behavior, such as slamming the bucket or hitting other equipment, and reducing the student's score accordingly.

Practice and Assessment

To support efficient training, CEVT simulators must first teach students what they need to know and do and then assess their knowledge and skills prior to allowing them to transition to the next level of

training. The CEVT HyEx simulator supports this through the use of practice and assessment modes.

In practice mode, students are first provided with background information describing the general task to be completed, the objectives of the lesson, and how they will be scored. Students then use hints, cues and warnings provided throughout the practice mode to help them learn proper techniques and safety habits (see Figure 6). While lessons in this mode are scored, these scores are not permanently stored in a database. This allows students to learn and practice without the pressure of attaining a passing score (that comes later).



Figure 6: Warnings, hints and visual cues guide students in practice mode

Once students have gained the knowledge, skills, and confidence for a particular task, they move on to the assessment mode. In this mode, students are expected to have learned the proper techniques and understand the potential safety hazards and how to avoid them. Therefore, the number of hints, cues, and warnings are minimized. At the end of an assessment mode lesson, a permanent score and report are generated and stored in the shared database. As shown in Figure 7, each lesson report includes relevant metrics and scores based on acceptable limits set by an instructor in a configuration file.

Emphasis on Safety

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 jobsite. As such, each CEVT HyEx training lesson includes potential safety hazards that students must recognize, and situations to which they must respond appropriately. Safety hazards tracked during lessons include swinging the excavator bucket over truck cabs or buildings, maneuvering inappropriately near open

trenches, improperly maintaining load limits which might cause the excavator to tip, maneuvering without first honking the horn, digging too close to underground utilities, swinging loads excessively, improperly loading the equipment on a trailer for transport, and operating too close to personnel or power lines.

James Smith
Class 2
June 6-8, 2009
Lesson 5: Dig a Level Trench
Control Pattern: ISO
Attempt: 1

Description	Ideal	Actual	Points
Max deviation from center	0m (0in)	0m (0in)	-
Time	05:00	05:00	-
Total volume removed	15.0yds ³	18.0yds ³	100
Material Above Grade	0.0yds ³	0.0yds ³	0
Material Below Grade	0.0yds ³	0.0yds ³	0
Equipment Damage	0	0	0
Bucket Slams	0	1	5
Lesson Score			95

Figure 7: Detailed Lesson Report

To build proper safety habits, the CEVT HyEx provides students with real-time warnings during practice mode. For example, if an operator approaches power lines with the boom elevated, the system will prompt the student to lower the boom before a safety violation occurs (see Figure 8). In this way, students learn to recognize potential dangers and correct their behavior to avoid accidents. Students are later tested on their knowledge of safety hazards in assessment mode. During assessment, warnings are not provided forcing students to recognize hazards just as on a real jobsite. A zero-tolerance approach is applied during the assessment mode. If a safety violation occurs, the student must repeat the entire lesson. This scoring approach provides a constant reminder that while productivity is important, safety is the top priority.

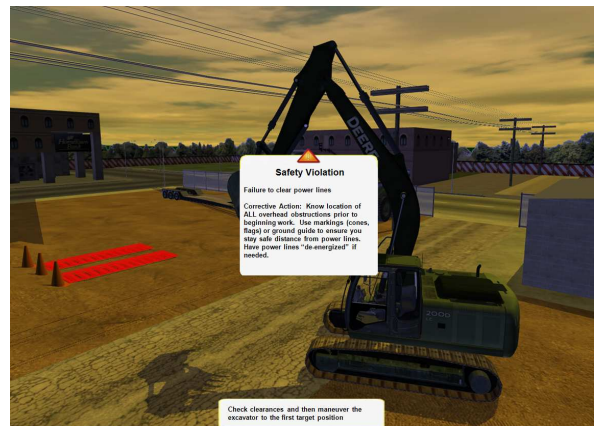


Figure 8: Safety Violation

BENEFITS

The CEVT HyEx simulators have been installed and are currently being integrated into the Program of Instructions (POI) at Fort Leonard Wood. Based on initial feedback, it is believed that the simulator will provide several benefits, including those listed below:

- By exposing students to operating techniques in a phased approach, students will have greater awareness, confidence and proficiency by the time they reach the hands-on training
- The ability to assess students' capabilities will allow instructors to quickly identify students who need additional training versus those who are ready to move on to the next phase making the whole training process more efficient
- By providing an alternative during inclement weather, students will be provided additional training opportunities and face less down time
- Because the simulator requires minimal interaction from an instructor, instructor/student ratio during initial training may be reduced allowing more instructors to support hands-on training

These benefits will ultimately reduce the number of actual machines needed for training. Initial estimates indicate this could reduce operating hours and maintenance by 5% – 10%, or more. This, in turn, will significantly reduce operating and maintenance costs.

FUTURE PLANS

Additional Level 1 Simulators

While the CEVT HyEx provides an effective means for developing and assessing students' abilities to operate a hydraulic excavator, this is but one of the many pieces of equipment students must learn to operate in the field. In addition to the HyEx, Fort Leonard Wood provides training on the following types of equipment:

- 4 Wheel loader
- Motor grader
- Bulldozer
- Scraper
- Mobile crane

Initial training on each of these pieces of equipment faces many of the same challenges as those faced on the HyEx. Students learning to operate these machines would equally benefit from Level 1 training simulators. Plans are in work to obtain and integrate

additional simulators for this equipment into the current training.

Higher Fidelity Simulators

It is clear that Level 1 simulators will provide a strong foundation which better prepares students for hands-on training by increasing training opportunities. By reducing the need for actual equipment during initial training, these simulators allow the actual equipment to be used more efficiently for what it is best suited– training and assessment of deeper and broader skills. The addition of higher fidelity simulators which provide additional functionality will even further reduce the need for actual equipment to support hands-on training. Enhancements which may be addressed by these higher level simulators would include:

- Additional environments/distributed simulation
- Enhanced terrain modeling
- Integration of motion platforms
- Enhanced depth perception cues

Additional Environments / Distributed Simulation

The relatively simple environments provided by the Level 1 CEVT HyEx simulator are more than capable of supporting initial training. However, by incorporating more sophisticated environments and integrating common Army simulation tools such as the Synthetic Environment (SE) Core, OneSAF and related products, future CEVT simulators will provide more in-depth training opportunities. By modeling actual deployed locations and allowing operators to participate in joint exercises, CEVT simulators may improve operators' understanding of safety hazards and operations specific to an actual location and potentially allow them to rehearse in coordinated construction operations prior to deploying, in much the same way as is currently done for simulated combat missions.

Enhanced Terrain Modeling

The CEVT HyEx simulator allows students to learn and practice basic earth moving techniques by allowing them to modify terrain surfaces modeled using a single basic soil type. Further enhancements in terrain modeling, such as those outlined below, will be necessary to support a broader range of training:

- Incorporating advanced dynamic terrain modeling capabilities which allow the equipment to maneuver the equipment over disturbed areas
- Simulation of a broader range of soil properties allowing operators to learn how various soil

types and conditions affect equipment performance

- Modeling of localized hard spots/rocks including random mixtures of clumps and fine loose soil
- Parameterized material properties which allow a configurable range of soil types
- Impact of soil type on equipment performance (i.e., traction, load carrying capabilities)

Addition of Motion Platforms

To minimize space requirements and life cycle costs, motion was not included in the Level 1 CEVT HyEx simulators. However, motion cues play a key role in more advanced training and will be required for future higher fidelity CEVT trainers. The specific types of cues and associated fidelity needed to model earth moving activities will need to be determined and the most appropriate level of simulated motion which provides an acceptable balance between life cycle costs and capabilities will need to be identified. In general, motion platforms will be needed to provide cues for the following:

- Accelerations associated with maneuvering over flat and sloped terrain
- Operating with an unbalanced load/onset of tipping
- Vibration associated with normal/abnormal equipment behavior
- Effect of bucket/soil interactions and stalling on equipment motion
- Indications of collisions

Enhanced Depth Perception

Because of the way operators are required to manipulate their equipment, visual cues, particularly those associated with depth perception, play a key role in the simulation of construction equipment. Operators must be able to accurately ascertain the location of equipment buckets/blades relative to the ground, in addition to being able to judge the depth of trenches. The simple display approach used for the CEVT HyEx provides a cost-effective method for supporting basic training; however, more sophisticated methods will support more advanced training. The use of various techniques such as stereo vision, wide field of view displays, head tracking and advanced 3D graphics will be evaluated to determine the most cost effective method for providing visual cues not supported by current simulators.

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