REFLECTIONS ON USING A GAME ENGINE TO DEVELOP A VIRTUAL TRAINING SYSTEM FOR CONSTRUCTION EXCAVATOR OPERATORS

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ABSTRACT: Virtual Reality (VR) technology can facilitate training in construction equipment operations, as the cost for virtual training is lower and the practical hazard is eliminated. This paper presents a virtual training system (VTS) for construction excavator operators based on a game engine tool. The focus of this paper is not to present a simulator that replaces those existing tools on the market, but to describe the development of a prototype for testing skill acquisition and transfer. The study reflects the experience of using a game engine to develop a VTS for an earthmoving excavator in a construction site. The development was initiated after exploring critical aspects of training. This paper also elaborates the principles of constructing a virtual excavator simulator based on the Unity3D game development engine.

Keywords: *Simulator, Skill Acquisition and Transfer, Virtual Training System*

1. INTRODUCTION

Concurrent with the popularity of gaming systems that utilize high-resolution graphics, simulator systems for training operators of specialized equipment are becoming more prevalent in the marketplace. Training for the operation of construction equipment is one of the leading applications because of the obvious benefits of reduced cost and hazards associated with training on real equipment in real field conditions. The general notion is that initial training in the simulated or virtual environment (VE) can save some of the trials and associated resources and exposure to hazards in the real-world practice phase that still must follow to ensure proficiency under real conditions. In addition, the game-like objectives inherent in such tasks as earthmoving and driving make the simulator technology appealing to the high-technology-oriented younger generation of would-be construction equipment operators.

Much research has been conducted in human factors and ergonomics relating to fidelity of flight simulators and design of effective training routines (Koonce & Bramble, 1998). Driving simulators of various fidelities have also been used to train student drivers and evaluate issues concerning vehicle and road design in safe environments (Boyle & Lee, 2010). Most recently, the medical community has turned to the use of simulators to create noncritical environments in which, for example, surgical procedures can be practiced (Dunkin, 2010). However, there have been few rigorous investigations of the applications of heavy equipment operator training simulators for the construction industry. When the topic is found in the published literature, the focus almost always is on technical aspects of prototype systems rather than on learning or transfer of training (Dopico et al., 2010). Of the skill-oriented studies, Hildreth and Stec (2009) verified transfer and examined the influence of motion feedback on transfer, and Kamezaki et al. (2009a; 2009b) emphasized using the simulator to study how the operator's control of a real machine could be improved through cognitive aids. As the use of VR-based simulators is becoming more widespread, in the present article we consider simulator applications for training of heavy equipment operators—primarily operators of earthmoving equipment such as backhoes and loaders—a topic that has tended to be neglected in human factors and ergonomics.

2. SKILL ACQUISTION AND TRANSFER

The general literature on skill acquisition divides skill types into sub-domains that overlap considerably and are often distinguished in name only for "heuristic convenience" (Newell, 1991). However, the general use of the comprehensive term perceptual-motor skill is commonly used to capture the relation between cognitive and perceptual elements that are related to the performance of motor tasks. Wang and Dunston (2005) also use the term sensorimotor skill instead of pure motor skill to underscore the element of a feedback loop that is present even when executing a simple motion control. The operation of construction equipment falls into this category or combined cognitive and motor skill application due to its nature of manipulative activities of the hands in the context of interacting with the work environment or objects in that environment to fulfill a designed task.

When it comes to specifically defining skill in the operation of construction equipment, the parameters of skill are not a completely settled matter, although some consistency of thought is emerging. It is understood that motor skills cannot be measured directly, but are inferred by observing behavior or performance (Wang & Dunston, 2005). Objective methods refer to the quantitative measurements such as performance time and accuracy, whereas subjective methods refer to such qualitative assessments as quality of output, consistency of operation, proactive thinking, adaptability to changing environments, capability for skill improvement, and with the opinions of experts. The actual measurements of skill in the proposed experimental program will vary depending on the selection of the test task and the essence of the skill.

The next issue concerns the nature of the skills that need to be acquired and transferred from virtual training. Bernold (2007) proposed that this issue needs to be considered from a performance perspective and a coaching perspective. He indicated that the performance assessed how well the trainee was learning to execute the training task(s), and coaching was the real-time feedback intentionally provided to enhance learning. Bernold also spoke to this matter, suggesting that the performance perspective should consist of high quality output (speed and accuracy), consistency of operation and smoothness of bucket motion, and the elements such as proactive thinking and reinforced learning should be involved in the coaching perspective. We conceived, designed and implemented the functionalities into our simulator to train and measure the above skills from both performance and coaching perspectives.

- High quality output (speed and accuracy)

In pursuit of speed and accuracy, our virtual training system (VTS) sets a timer to calculate the time consumption of each earthmoving (from earth stockpile to truck) and generates a viewpoint for observing earth drop (outside of truck). Fast earthmoving might make the earth fall onto the ground during moving while to the opposite, slow earthmoving might take too much time. If failing to obey the operational accuracy, the trainees are not able to dump all the earth into the truck with a satisfactory volume.

- Consistency of operation

The consistency of operation means hands and feet coordination. Our VTS formulates an earthmoving environment, as real as the actual work. The trainee always needs to put his foot down, drive the machine, and make the scoop shovel up the soil from the convenient angle according to his/her hand movements.

- Smoothness of bucket motion

Bucket motion should be very smooth. Any sudden rotating or moving the bucket could make soil drop out from the bucket. Specifically, when lifting up the boom and swing or driving the excavator along the rough road, the trainee should synchronously balance the bucket to prevent from earth dropping.

- Proactive thinking

Proactive thinking from the coaching perspective is a newly raised skill that needs to be transferred from our

VTS. Although not being fully realized yet, our VTS has proposed a scenario that before training in the VTS, the trainee should conduct some planning in the aspects of safety issue, breakdown treatment, false operation and so on.

- Reinforced learning

Reinforced learning is a critical skill in decision making. How to make a proper decision during earthmoving is based on what a trainee perceives to be the most valuable or worthwhile actions. This is determined by what he/she finds to be the most reinforcing stimuli. On the basis of this, our VTS is constructed to be able to provide essential rewards and/or helps in the form of tips or suggestions during operation or after, and reinforce the trainee what is learned after training.

3. AN INTEGRATED TRAINING PROGRAM

We use the term "simulator" to refer to any mock-up of the real equipment that consists of manual and pedal controls and the display of a real-time, interactive, computer-generated, three-dimensional scene that shows an operator's egocentric view from inside their equipment and the material that is to be handled or processed. They are dedicated essentially to the creation of compelling interactive virtual environments within which human participants are led to feel somehow present, for purposes of training. Based on VR or gaming software technology, these systems may also be programmed to provide realistic sounds, haptic feedback through an actuated platform underneath the operator's seat, and additional non-egocentric views of the equipment and work site. Although only parts of the components involved in the interactive training environment are simulated, the operator nevertheless can experience a similar sense of presence from interacting with real/virtual objects via visual, auditory or force displays.

VR-based simulators can be especially valuable where training in real-world situations would be impractical because such training would be unduly expensive, logistically difficult, dangerous, or too difficult to control. The work scenarios are displayed on desktop, laptop, or large screen monitors (single or multiple). As the transferred skills are practiced, however, the real-world performance is compared against the virtual world performance to measure the degree of transfer. The benefit of such a programmed approach is that it automatically provides the trainer with a measure of the effectiveness of the virtual training phase with respect to each skill. The trainer, in the course of training new operators, can also make critical evaluations of the appropriate amount of time to spend in each phase and even assess, from historical data, how any new VTS compares against another.

4. SIMULATOR CONSTRUCTION

We selected Unity3D, a game engine, as a simulator construction tool because of its easy programming and versatility. Unity3D has an advantageous world building tool, user-friendly interface, and lots of target platforms (mobiles, web, PC/MacOS, etc. are supported). Meanwhile, editing, testing, polishing, and playing what have been developed are quite easy to achieve within Unity3D. Also, Unity3D supports easy scripting in forms of JavaScript, C# or Boo script. Users can retrieve different scripts that are open-sourced and formulate their own scripts according to the user manuals and scripting reference in Unity3D official website. Besides, the system can track and show bucket path based on Bernold's (2007) assertion of its importance. The section elaborates the programming challenges such as soil behavior modeling, capturing and documenting critical performance data, etc. Three-dimensional stereoscopic display is also briefly considered. Lessons learned from the research and development of this system can be generalized to other VR simulators for construction equipment operator training.

The following picture shows the Unity3D development interface for excavator (Fig. 1). Game and scene views can be randomly dragged in a separate part within user interface, while the hierarchy, projector and inspector views can be positioned in the right of the partition line.

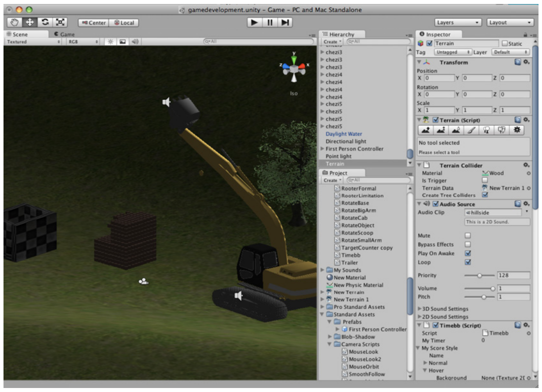

Fig. 1 An overview of interface for virtual excavator training simulator.

First of all, the virtual construction site was created using the 'terrain editor', a particular tool to create diverse terrains in Unity3D. 'Terrain editor' encapsulates the functions of raising/lowering the terrain, smoothing terrain, planting trees, defining wind and so on, in which arbitrary definitions of complex terrain are easy to obtain by users. In our preview, some trees are planted on the uneven grass ground. Since a critical requirement in terrain processing is to make a simulated environment closer to reality, some particular acoustic and optical effects are added into the scene, e.g., breeze, swinging trees, moderate sunlight, decent shadow and ambient sound.

After the creation of the simulated construction site, a patterned and accurate excavator needs to be placed inside it. Therefore, conforming to the real-scaled excavator components, a virtual prototype excavator was designed based on drawing software 3dsMax and formatted it as *.fbx file, which can be later recognized by Unity3D without exported mistake. At the same time, for alleviating modeling work, the surrounding immobile buildings were selected from varieties of online model resources and applied to the construction site (Fig. 2).

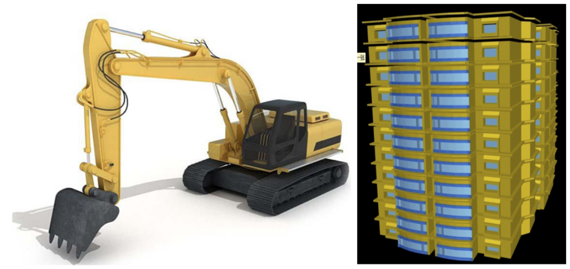

Fig. 2 Virtually constructed excavator and apartment building

Scripting is a critical process during the simulator construction. It realizes the functionality of each component of the equipment. In light of the structural complexity of equipment and considering that each component has individual movement characteristic, five major functional modules have been simplified out: the bucket module (close/dump), the swing module (right/left), the boom module (raise/lower), the cabin module (rotation left/right) and the base module (rotation/moving) (Fig. 3). The affiliation of each module is as follows: the bucket is connected to the swing, the swing is subject to the boom, the boom is based on the cabin and the base is on the top of the hierarchy (Fig. 4). The advantage of this affiliation enables locally-transformed scripts to be applied to each module while maintaining the relative spatial constrains of the five modules. Specifically, there is a function called Update, which will be called once. This is where most game behavior code goes, except physics code. Applying certain functions, e.g., Time.deltaTime, transform.Rotate, tranform.localEulerAngles, Mathf.Deg2Rad and so on, motion based on altering local coordination of each module such as angular velocity, rotation axis and spatial displacement can be formulated. More directly, in Unity3D developers are capable of applying varieties of default scripts that are commonly used in first person controller games, such as scripts for first person's walk (FPSwalker) and camera look. In our VTS, the base module and two cameras are assigned FPSwalker script ('jump' motion is invalidated, so the operator can only drive the excavator) and two camera-look scripts, respectively. Besides, a music track (mechanical boom) is assigned to the base module as well. It is typically triggered when driving the equipment, as same as the real case.

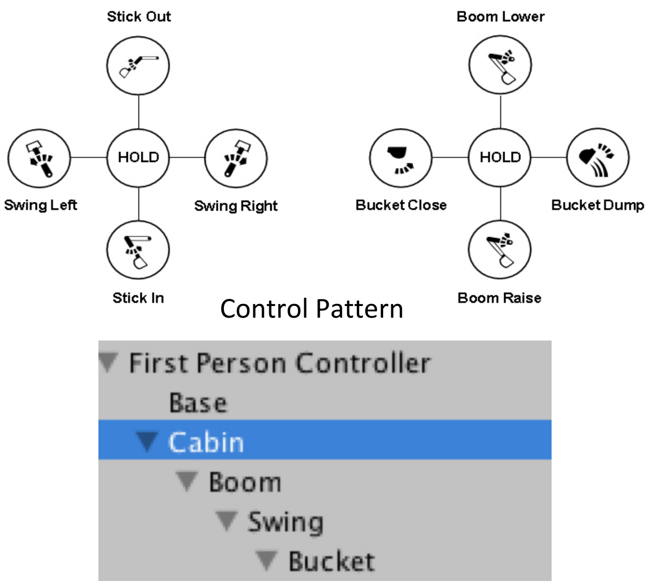

Fig. 3 Control pattern for excavator controls and a snapshot of hierarchical list for five modules.

Apart from the simulator construction, another critical issue is soil modeling. Unfortunately, since the Unity3D has not been an engine that fully encapsulates 'Physics' neither in its previous versions or in the latest released version, earth digging can only be approximately simulated in the forms of small grey boxes (Fig. 4). The flaws of this are obvious: simulation of earth digging has a certain level of distortion and numerous boxes are needed to be as a heap of earth which in turn increases the calculation burden of computer. However, a trade-off is to optimize the simulated earth. According to assigning constant mass, gravity, angular drag force, wrapping box colliders and freezing box rotation (since each box has a sphere collider, this can freeze the rotation when collision occurs), the simulated earth bears decent physics in the context of contact, bounce, penetration and friction.

Fig. 4 A snapshot of a heap of earth in game view in Unity3D.

Last but not least, the construction of VTS raises some specific requirements: be able to monitor, record, display bucket trajectory during digging, and be able to display stereoscopically from cabin perspective and bird's eye perspective. To achieve these, an invisible trail renderer is set on the left corner of the bucket, and a script for rendering the trail is added into the render so that the trajectory of the bucket edge can be spatially exhibited in terms of red arc. Besides, the main camera is realized by a positional switch between inner-cabin and outer-cabin (Fig. 5). Except the main camera, an aided camera for profile view is installed on the same level of the base and an inset window is created at the bottom of right corner for the trainer and trainee to inspect (Fig. 5). Also, monitor time of execution of a simple task can be real-time calculated and shown. The last thing is to make the system work with joysticks for directing the equipment functions. Fortunately, Unity3D enables the direct mapping between keyboard and joystick after building the game. Before each starting the VTS, user can modify the key mapping through the mapping interface. Now, the VTS is completed.

Fig. 5 Perspective patterns—outer-cabin view, inner-cabin view and profile view.

5. CONCLUSIONS AND FUTURE WORK

The two critical primary themes outlined in this paper are (a) understanding how virtual training technologies best support both the development and transfer of fundamental skills and (b) creating a usable VTS that supports complex and practical equipment operator training scenarios. The first theme will establish scientific principles that can relate appropriate virtual training technologies to the development of various real-world fundamental skills. Subsequently, experiments will be performed and the results for skill acquisition and transfer will be evaluated. Likewise, experimental results will make a better design of our VTS by informing the selection of appropriate information representation, computing devices, feedback devices, interaction tools, motion trackers, and communication devices. It is expected that this research will establish knowledge to significantly improve the effectiveness of off-site VTS and result in substantial long-term cost and time savings for operator training.

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