Virtual Reality Ladder Climbing for Mine Safety Training

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ABSTRACT: Safety is an important issue in the mining industry, and ladder safety is a significant yet often-overlooked aspect. In the U.S., more than a thousand slip and fall accidents occur at mining locations each year. Prior research indicates that more than a third of slips and falls occur while getting on and off equipment, machines, and vehicles. Root causes of these accidents appear to be inadequate training, the routineness of mounting and dismounting equipment, and an abundance of vertically fixed ladders that require extra caution. More effective solutions for training ladder safety are needed.

To address this issue, a virtual reality (VR) system for training safe ladder climbing strategies has been developed. This VR system uses a motion capture system to track and analyze the movements of the trainee’s hands and feet. A head-mounted display (HMD) provides an immersive view of the virtual mining equipment and a vertically fixed ladder. A three-dimensional interaction technique allows the trainee to virtually climb up and down the ladder. When the trainee does not use the three-point control strategy to safely climb, virtually restricted capabilities prohibit the trainee from improperly completing the training task. Since the training environment is virtual, adverse events can accompany the restricted capabilities, such as falling off the ladder and sustaining artificial injury. This highlights the potential risks stemming from poor physical form and decision-making to the trainee. The new VR training system has the potential to reduce the number of slip and fall accidents in the mining industry.

INTRODUCTION

According to the National Institute for Occupational Safety and Health (NIOSH 2013), approximately 29.3% of nonfatal lost-time injuries at surface mining locations were caused by a slip or fall between 2008 and 2012. A study conducted by Bell et al. (2000) indicates that more than a third of slip and fall accidents are ladder-related and occur while getting on and off of equipment, machines, and vehicles. Hence, around a tenth of surface mining accidents involve climbing a ladder. Outside of the mining industry, a large number of ladder-related accidents also occur. It is no surprise then that NIOSH has released the “Ladder Safety” mobile application for iPhone and Android devices (Spring 2013).

Many factors have been identified as root causes of ladder-related accidents. Workplace factors can include situations such as inclement weather, slippery surfaces, and poor lighting (ISSA 2008). Individual factors can include age, employee fatigue, poor eyesight, or inappropriate footwear (Anderson and Mulhern 2010). The Mine Safety and Health Administration (MSHA 2013)
has also identified a lack of training as one of the primary causes of such accidents. In particular, proper training that informs mineworkers to be aware of workplace factors and individual issues could significantly decrease the number of these accidents.

Beyond training workers to be aware of potential hazards and factors, training workers on proper ladder-climbing strategies is crucial. According to Ellis (2012), use of the three-point control ladder climbing strategy could prevent most injuries and deaths related to ladder falls. The three-point control strategy is a technique that involves methodically using three of the four limbs for reliable support while the other limb is being positioned. This is slightly different from just maintaining three points of contact, as a point of contact could just be the stomach, a palm, or a few fingers. However, a reliable support can potentially bear the full weight of the body if needed in an emergency, such as fully grasping a rung with a hand.

While the three-point control strategy can be communicated via traditional training methods (e.g., brochures, PowerPoint presentations, shadowing), it is not often practiced under the observation of trained safety personnel, nor is it easy to assess. However, by using virtual reality (VR) technologies, we have developed a training system that can communicate the three-point control strategy, enforce its use during practice, and emphasize its importance in a safe manner. Additionally, due to the nature of VR technologies and computer-based simulations, our system could be used to assess whether a mineworker is properly trained to safely use ladders on a daily basis.

The remainder of this paper is dedicated to describing our new VR system for training proper ladder climbing strategies and an off-highway truck application of the system.

**VIRTUAL REALITY TRAINING SYSTEM**

To address the aforementioned training issues, we have developed a VR system for training safe ladder climbing techniques. In the sections below, we discuss the system’s hardware components, a novel 3D interaction technique that affords realistic climbing motions, and the virtually restricted capabilities that enforce training concepts.

**Hardware**

Our VR system’s hardware consists of three primary components—a tracking system, handheld controllers, and a wide field-of-view HMD. For tracking, we have developed the system to be compatible with two different types of systems. The first system is an optical tracking system consisting of 16 Vicon MX cameras. Constellations of reflective markers define objects that the system tracks with sub-millimeter accuracy. However, the system is not portable due to the absolute nature of its camera setup and optical tracking capabilities. Therefore, the second tracking system that we have developed for was an inertial tracking system consisting of 17 YEI 3-Space sensors (seen in Figure 1). Each 3-Space sensor is an inertial measurement unit (IMU) consisting of a 3-axis accelerometer, a gyroscope, and a compass. These sensors provide accurate orientation data within a degree, which we have used to recreate the forward kinematics of the user’s motions based on anthropometrics and biomechanics. Both tracking systems allow us to track the positions of the user’s head, hands, and feet.

We use two Nintendo Wii Remotes to provide wireless handheld controllers. Each Wii Remote has an internal vibration motor for tactile feedback and 11 input buttons. We use only two of these input buttons (the circular A button on top and the B button trigger in the back) to keep
our system simple and ergonomic. Though Wii Remotes have their own 3-axis accelerometer and gyroscope, we use marker constellations to track these handheld controllers with the Vicon system and the two 3-Space hand sensors with the YEI system, as both of these systems are more accurate than the Wii Remote.

The current version of our VR training system uses an Oculus Rift Development Kit 1 (DK1) HMD for a visual output display. The DK1 provides 360° head tracking and a 110° field of view (FOV). Its form factor is goggle-like with elastic straps and only weighs 379g. The primary limitation of the DK1 is its low resolution of 640×800 per eye. However, we are currently investigating the new Development Kit 2 (DK2), which offers a higher resolution of 960×1080 per eye.

Climbing Interaction Technique

The centerpiece of our VR training system is a novel 3D interaction technique that simulates climbing a ladder. We designed this technique by analyzing the kinematics and contacts involved with climbing up and down a real ladder.

For climbing up a real ladder, the mineworker begins by grabbing ladder rungs shoulder level or higher, as seen in Figure 2A. We duplicate this process by requiring the user to reach out with the Wii Remote to grab the virtual rung by pressing A and B on the controller (Figure 3A). When grabbing a rung, the user’s virtual hand remains in place (see Figure 3C) until the user releases the A and B buttons. Next, in the real world, the mineworker raises a foot up to step on a lower ladder rung (Figure 2B) and steps up off the ground (Figure 2C). We mimic this by having the user raise and lower his or her foot as if marching in place. When the user’s virtual sole comes in contact with a virtual rung while being lowered (Figure 3B), our technique simulates the user stepping up. By raising the position of the user’s virtual body within the virtual environment (Figure 3C), the user perceives being on the virtual ladder rung, despite still physically standing on the ground (notice the virtual ladder rung below the physical ground). Due to the lack of force feedback when stepping
on the virtual rung, we display the user’s virtual feet 25 cm in front of their physically tracked positions to provide the user visual feedback of contacting the rung.

For climbing down a ladder, the mineworker progresses by stepping down one ladder rung with one foot and then the other foot, as seen in Figure 4. Since the user would still be on the ground, replicating this would not be possible with our system. However, we were able to mimic the kinematic motions of the legs by reusing the marching-in-place concept and reversing the direction of the virtual climbing motion. When the user raises his or her foot, the position of the user’s virtual body is lowered within the virtual environment until the other virtual sole (physically on the ground) comes into contact with a virtual rung (Figure 5B). At this point, virtual climbing is disengaged until the user’s raised foot comes back in contact with the physical ground (Figure 5C). To distinguish the same marching in place motions for climbing down from climbing up, the technique requires the user to grab rungs with only the B button (i.e., not the A button) to climb down.
While previous 3D interaction techniques have addressed ladder climbing by utilizing walking in place (Slater et al., 1994) or reaching (Takala and Matveinen 2014), this is the first technique to combine the two into a realistic set of kinematic motions for climbing virtual ladders.

Virtual Restricted Capabilities

To be realistic, our novel climbing technique only requires two points of contact (one hand and one foot) to stay on the virtual ladder. However, mineworkers should be trained on the three-point control strategy for safely climbing ladders, which requires at least three reliable supports. Hence, we have designed two techniques that virtually restrict the capabilities of the user to enforce training concepts. We call these techniques “virtually restricted capabilities.”

Our first virtually restricted capability focuses on enforcing the proper three-point control strategy. Though our basic climbing technique allows only two points of control, this restricted capability requires that the user have three points of control (two hands and one foot) to virtually...
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climb up or down. If the user does not have three points of contact, the virtually restricted capability ignores any marching-in-place motions. Hence, this training strategy is designed to enforce the proper climbing technique, as the trainees will not be able to virtual climb up or down otherwise.

Our second virtually restricted capability focuses on emphasizing the importance of the three-point control strategy. When the user attempts to climb up or down with our climbing technique, if three points of virtual control are not maintained, a virtual fall is simulated. During this fall, the position of the user’s virtual body is quickly lowered to the virtual ground and the mapping between the physical space’s orientation and the virtual environment’s orientation is changed. Essentially, the mapping is rotated 90° backwards, which directs the user’s view toward the virtual environment’s sky. Users perceive these mapping changes as falling off of the virtual ladder and landing on their back, despite safely standing in the real world. This training strategy is designed to emphasize the importance of ladder safety and the possible consequences of improper climbing practices.

OFF-HIGHWAY TRUCK APPLICATION

To investigate the usefulness of our VR ladder-training system, we have developed an off-highway truck application. Many off-highway trucks have operator cabins situated high above the ground that require ladders or steps to access. Many truck models are fitted with vertical ladders. Since off-highway trucks are used heavily in surface mining, and climbing up and down these ladders is an unavoidable daily task for the truck drivers, we chose to use mounting and dismounting an off-highway truck as the first application scenario for our new VR training system. We have modeled a Caterpillar 777D truck, which has two ladders located in the front that provide access to the operator platform above. These ladders have several rungs and are slightly slanted, which are good tests for our novel 3D interaction technique.
CONCLUSION AND FUTURE WORK

In this paper, we have presented a new VR system for training the three-point control strategy for climbing ladders. The system can utilize one of two different tracking systems, handheld controllers, and a wide-FOV HMD. We have developed a novel 3D interaction technique that closely simulates the kinematics of climbing a real ladder, but without physically leaving the ground. To enforce practice of the three-point control strategy and to emphasize its importance, we have also developed two virtually restricted capabilities. The first enforces the strategy by not allowing the user to virtually climb without maintaining three reliable supports. The second emphasizes the importance of the strategy by simulating a dangerous fall when the user does not maintain three points of control to climb the ladder.

For future work, we have several plans. First, we plan to evaluate the effectiveness of our VR training system by comparing it to the Ladder Safety smart phone application released by NIOSH for iPhone and Android devices. We will conduct a between-subject experiment with two cohorts of trainees (our VR system and the smart phone app) that are brought back later for a real-world ladder climbing assessment to determine which training method is most effective.

In addition to evaluating the effectiveness of our system, we plan to extend it by developing scenarios that would normally be unsafe to practice. Examples of such scenarios include wet rungs due to rain, footwear with worn or clogged treads, and partially broken ladders with missing lower rungs.

REFERENCES

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