

Interaction and Ergonomics Issues in the Development of a Mixed Reality Construction Machinery Simulator for Safety Training

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Abstract. We present the work on a simulator of construction machinery developed to train workers in their safe use. The simulation setup consists of a real versatile cabin placed on a motion platform in order to provide a realistic interaction with the system and a stereoscopic augmented reality system for visualization. We present some insights into the mixed reality setup we used for complex construction machines and discuss the interaction and usability problems that have arisen during its development and testing. Visualization has been implemented as a chroma-key-based mixed reality system, which combines the 3D virtual environment, the real cabin interior, and some superimposed messages to the user. As a result of our experience, we describe the main problems encountered from a usability and ergonomics point of view.

Keywords: Interaction, Ergonomics, Mixed Reality, Construction Machinery, Simulator, Safety, Training.

1 Introduction

The use of simulators as training tools for machine operators is spreading rapidly. Although some years ago simulators were mainly used for leisure and in the defense and aeronautics sectors, in recent years their use has also extended to new areas such as construction [1] and the automotive sector [2][3][4][5].

When the simulation of machines is targeted at training people, the realism of the simulation becomes a relevant aspect. This realism is closely related to the way in which the dynamic behavior of the machine is modeled in reaction to the operator commands, the visual quality of the simulated construction site scenario, and to the interaction between the machine and the virtual working environment.

The paper describes work done in the European Collective Research project VAR-Trainer from a usability and ergonomics point of view. In this project dynamic models of four different types of construction machinery have been developed (wheeled excavator, dumper, work goods lift and mast climb platform). The project aimed at

the creation of an affordable training platform for construction operators focusing on safety at work, based on the use of real-time simulators and a mixed reality setup.

First, some related works are commented followed by the VAR-Trainer architecture explanation. Next, the results of user tests are shown. Finally, some conclusions and the future work are presented.

2 Related Work

Despite nowadays the use of machine simulators for training purposes is expanding in different fields, there is virtually no commercial simulator for training workers in the safe use of construction machinery, which takes into account the pedagogical aspects by design and not like an added value to the product or such a technology is not commonly used by educational entities.

One of the products of CMLABS [6] is a harvester simulator for training, consisting of an articulated vehicle for traversing uneven terrain and a boom with a complex head to cut and manipulate tree trunks used to fell trees, de-limb and cut them.

The Institute of Robotics Research [7] has developed another harvester simulator, which may be used with different display equipment (passive stereo projection, shutter glasses with a monitor or head mounted display (HMD) with tracking system). It is based on the virtual reality simulation system (COSIMIR/VR) and has been used in the development of some excavator simulators.

The training simulator of hydraulic excavator (SHE) project [8] implemented an immersive simulator prototype of an excavator based on a motion platform on which a fake cabin is assembled. The virtual reality system provides sensations resembling the use of an actual excavator, but studying ergonomics and interactions issues was not the major goal.

3 VAR-Trainer Architecture

The main goal of the project VAR-Trainer is to develop a versatile real-time simulator, based on the integration of mechanics, electronics, automation technologies, and mixed reality (virtual & augmented reality) in order to train workers in the safe operation of construction machinery [9].

Most of the available simulators are specifically oriented towards a single machine or process type and are not open reconfigurable platforms able to adapt to different machine types, different levels of realism or different pedagogical aspects. Besides, machine training simulators usually aim at covering the training in all the machine's functionalities and are not focused on specific training aspects, such as safety.

The developed training simulator is sufficiently versatile and user-friendly to train in different types of construction machinery: lifting equipment (work goods lift), aerial work platforms (mast climbing platforms), and heavy works hydraulic machinery (wheeled excavator and dumper) (see figure 1). In the rest of the paper we will focus on the Mixed Reality setup and the interaction and ergonomic issues.



Fig. 1. Hardware setup: Exterior (left) and interior view (middle) of the real excavator cabin used for excavator and dumper simulation. The blue-box used for mast climb platform and lift simulation, also mounted on the motion platform (right).

3.1 Hardware Setup

Driving simulators typically use large projection screens where the virtual environment is displayed, but augmenting real images with additional information requires a different design. The use of real cabins mounted on a motion platform limits this approach, since the external projection screen should be huge to provide an immersive environment.

Another approach considered was to mount flat panel screens replacing the windows in the cabins which eases the virtual reality rendering but increases the total weight on the mobile platform. Stereoscopic vision would be nearly impossible.

In our system, the mixed rendered stereoscopic view is displayed using a video see-through head-mounted display (HMD) specifically designed [10], while the machine cabin and its controls are the real devices. The main elements of the setup are described in the following sections.

3.2 Virtual Reality

The virtual reality scene consists of virtual elements and their physically-based behavior and interactions. A specific subsystem simulates the dynamics of the driven machine and the interaction with the operator via the cabin controls [11][12]. Another module deals with the physics and visualization of the virtual environment. Some of the main tasks of the virtual reality system are the animation of vehicles and human characters, collision detection and vehicle-ground interaction, simulation of excavation and rendering in different weather conditions.

Safety issues when operating heavy construction machinery are also related to environmental situations like lighting and weather conditions and to the nature of the soil on which the machine is operated. Thus, particular care was taken to achieve a realistic perception of the virtual construction scenario [13][14] (see figure 2). Therefore several GPU shader programs have been implemented.



Fig. 2. Virtual reality. The virtual scene has been implemented using OpenSG as the graphics engine and ODE for the physical behavior. GPU shaders have been used to render the weather conditions (rain, fog, clouds) and the soil to enhance the realism of the scene.

3.3 Mixed Augmented Reality

The adopted mixed reality setup for visualization is motivated by the different layers of information that should be visible to the user, keeping low hardware costs [15].

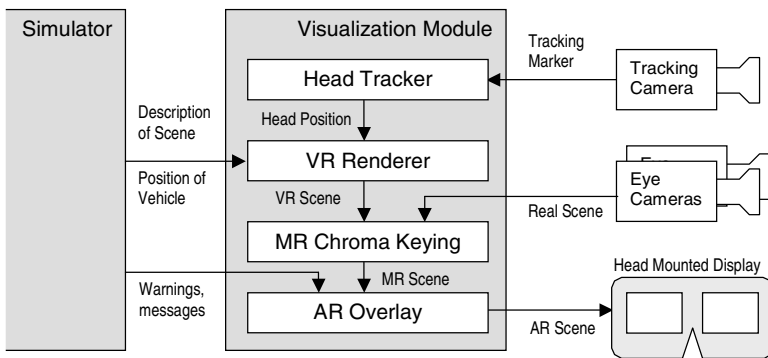


Fig. 3. Mixed reality architecture. Two cameras mounted on the HMD capture the real images, which are combined with the virtual reality and rendered in the same position using the tracking data. Finally, the augmented messages are superimposed and this final image is shown to the user. These steps are performed for the left and the right eye independently.

These layers are: (i) the virtual construction site scenario and the virtual part of the vehicle being the virtual background of the scene, (ii) the real parts of the cabin in front of the virtual scene, i.e. the real foreground, and (iii) the augmented messages on top of the real foreground to display messages or to provide hints (see figure 3).

The combination of the second and third layers represents the classical augmented reality (AR) situation, where a real background is augmented with virtual superimposed elements. The main approach here is the opposite: the background is virtual and the foreground (the cabin and everything inside) is real, with an additional virtual layer on top.

Once we have a composed image for each eye, they are augmented with the additional text that will inform and help the trainee with messages and hints to properly carry out the assigned exercise. Special care must be taken in the integration of 2D and 3D information in a stereoscopic visualization system, otherwise unpleasant depth perception effects show up.



Fig. 4. The eMagin Z800 HMD has been modified by adding two Firewire cameras to capture one image for each eye and an active marker that is used to track the user position. The total weight of this first prototype setup is about 350 grams but it could be reduced in the final setup.

3.4 HMD

Because of the costs, driving simulators are typically equipped either with monoscopic non-immersive visualization systems, or with a head mounted display (HMD), the latter reducing the visual quality because of the common low resolution and limited field of view.

Historically HMDs have introduced different ergonomic problems. This aspect has to be taken into account. Not all HMDs are comfortable to wear due to excessive weight, shape or troublesome cabling, or bad resolution. The HMDs technical characteristics and the achieved stereovision effect are also very important. Continued use of HMD devices and stereo displays is known to produce potential problems such as sickness or disorientation.

For VAR-Trainer (see figure 4), however, the decision had to be in favor of a low-cost fully stereoscopic immersive setup, as it is mandatory to provide a full panoramic view outside the cabin and because of the importance of depth when accomplishing a given training task. The used HMD partially overcomes or improves some of the limitations stated above. It is the eMagin Z800 3D Visor that consists of two high-contrast SVGA OLED microdisplays delivering a bright, crisp image, and with less than 230 grams being compact and comfortable. The image covers a diagonal field of view of 40 degrees.

The first HMD prototype has two cameras mounted on it, in order to capture the images from the user's point of view. The captured images are processed to adjust the field of view of the camera to that of the visor, and to correct any possible optical distortion.



Fig. 5. Chroma-key: Original image (left) and final image, after blue screen matting (right)

3.5 Chroma-Key Technique

The images captured by the cameras on the HMD must be correctly mixed with the virtual reality scene. Therefore, the blue screen technique has been adopted, also known as chroma-keying. Blue screen is a film-making technique of shooting foreground action against an evenly-lit monochromatic background for the purpose of removing the background from the scene and replacing it with a different image or scene. The blue filtering is easier if the blue color range is determined and stable.

In VAR-Trainer, (see figure 5), the blue screen itself has been realized by coating the windows of the cabin with a translucent blue foil. Some illumination and filtering problems appeared, disturbing the user's perception, and fine tuning of the system was necessary. The addition of some diffuse lights in the interior producing uniform blue surfaces which can be easily filtered greatly reduced the problem.

Additional problems arise due to the chroma subsampling, which reduces color resolution.

Although the cameras mounted on the HMD deliver a high-quality image which is very pleasing when viewed on a screen, the image quality in the cabin setup could be further improved. In conjunction with the blue screen matting, some artifacts appear. They could be removed by using a pair of lightweight cameras, which do not make use of the chroma compression technique like the ones used in this project. Nevertheless, the current image quality is quite good and the artefacts do not disturb the perception of the immersive environment too much.

3.6 Optical Tracking System

The virtual world must be rendered from the user's point of view provided by some head tracking system. In VAR-Trainer, a low cost one-camera optical head tracking solution developed at IGD, was used [16][17].

The optical tracking was the most suitable tracking system since the movement range of the user's head is limited and a wide angle lens was sufficient to cover the excavator cabin. Magnetic tracking was tested but, as expected, the tracking error was

too big due to the distortions introduced by the metallic structure of the cabin [18]. The movement of the cabin during operation also forbids relative tracking systems e.g. using inertial sensors.

The infrared camera is installed in the cabin's ceiling on a special box on the roof looking down, where the relation between tracking stability and tracking area coverage is maximized. An active marker (with infrared LEDs) was attached on top of the HMD prototype due to its higher reliability compared to reflective markers. Our tracking software calculates head position and orientation based on the camera view of the marker.

The tracking system's accuracy is acceptable for this application, although some instability, particularly in the roll angle, is perceived which can add uncomfotability. Inaccuracy increases as the user moves away from the central sitting position but such a movement is likely to be small or infrequent.

4 Results

The simulator setup has been tested by a group of users with different profiles, all of them sharing a background on construction machinery and safety at work. The group tested the excavator and the platform simulator, providing their impressions about realism, usability, ergonomics and usefulness.

Previous to these final tests some experiments have been made to analyze the importance of realistic rendering of the construction site.

4.1 HMD Ergonomics

The first time testers put the AR-HMD on, most of them felt uncomfortable, since they had never tried such a device. However, after some time, this feeling mostly disappeared. As the simulation went on, most of the testers encountered some strange sensations in the neck and head due to the weight of the HMD. Although its weight is not excessive, the usage of the HMD during large sessions causes this kind of side effects. Another impression of almost all users was the hot feeling when they were wearing the HMD, but the testers with some VR devices experience commented that the chosen model is not as hot as others. This sensation is increased in the platform setup, since the cabin is completely closed lacking proper ventilation.

After all, the group of people taking part in the trials considered the HMD quite comfortable and commended its image quality.

4.2 Virtual Reality, Augmented Reality and Chroma Key

All testers were surprised by the effect of the virtual and augmented reality mixed in the visor. It is certainly a strange sensation to see the real world including our own hands through cameras while also seeing the nonexistent outside environment through the windows. The users quickly got used to the system and found a very convincing stereoscopic effect. These features combined with the motion platform offers a fully immersive and realistic simulation of construction machinery.

The testers found some problems related with superimposed texts. Since they are rendered at the zero-parallax plane, they may be perceived further away than objects behind them, resulting in a very strange effect. The depth of text overlays must be correctly set to a closer plane.

As expected, the lighting conditions affect the quality of the chroma key image composition. It is very important to get a uniform blue in the images captured by the cameras, in order to be able to substitute the bluish pixels with the virtual reality image. Insufficient or non-uniform lighting causes glittering or blinking of some frontier pixels. During the trials, the testers noticed some of these artifacts when they were looking at the darkest areas of the cabin. Specular highlights on the blue surfaces were another source of problems as the white reflected light changes the light hue and saturation passing through the blue filter unaffected.

During tests taking place earlier users were asked to evaluate the realism of different parts of the construction site scene [14]. The scene was presented twice, first using the HMD (immersive), and second using a 17-inch monitor.

The results of the experiment showed that shaders bring more realism, but they also showed that some visual effects are highly application dependent. For a mostly static environment where the viewer does not often look up into the sky, a less sophisticated static sky rendering is sufficient. Furthermore, the rendering appears to be more realistic when presented using a HMD instead of a standard monitor.

4.3 Optical Tracking System

The tracking system is the element of the setup that made the testers more uncomfortable. When they did some very aggressive movements or moved out of tracked area, they noticed that the image got frozen, because the tracking system lost the user's point of view. After some training, the users learned where they can move their head, and this problem was reduced. In the platform setup, this effect is dramatically increased because the users are standing up and they tend to walk in all directions, causing frequent tracking failures. In this case, it is more difficult to teach the user to stay in the tracked area.

The tracking system has an inherent instability (even with the user at an optimal position) that should be limited to tolerable ranges. The inclusion of image stabilizer filters can improve the user experience, but in this case, no filter additions were needed, as the achieved tracking stability is enough.



Fig. 6. Screenshots taken during the trials. A dumper exercise (left) and an excavator exercise (middle) from the user's point of view. A user testing the system (right).

5 Conclusions and Future Work

This work has presented a construction machinery simulator with a mixed reality setup (virtual and augmented reality) aimed at training workers (see figure 6).

The tests have provided useful information about which aspects of the simulator should be improved. The optical tracking has been the module that has received the most remarks from the users. Despite this, the overall impression of the testers has been positive.

The deployment of the simulator to be used in different places is one of the future work tasks, where the simulator will be tested by skilled real trainees that should be instructed previously in its correct use. This phase will be used to improve the automation of the simulation deployment process, including lighting configuration and other aspects. Trainees will provide interesting additional feedback about the simulator usability.

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