A Fully Immersive Virtual Reality Training System for Rocket Fuel Mixing Operations

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ABSTRACT

MYMIC Simulations and Orbital ATK developed an immersive virtual reality demonstration environment to potentially train personnel on rocket fuel mixing procedures because Orbital ATK needed an effective way to provide immersive, effective training on hazardous operations. MYMIC and Orbital ATK developed a concept prototype using a head-mounted display to deliver a fully immersive 3D training experience. The implementation integrates Oculus Rift and Unity 3D with an Xbox360 controller. Beta testing of the prototype was positive and constructive realism was experienced; trainees attempted to reach out and touch portrayed objects as well as dodge ones that were too close. The training incorporates a virtual instructor avatar that orients the trainee. Lessons learned as to the efficacy of using virtual reality for training scenarios and development challenges are discussed.

ABOUT THE AUTHORS

Thomas Mastaglio, Ph. D, MYMIC, Dr. Mastaglio is the Chairman of the MYMIC group of companies, small businesses specializing in professional services, modeling, simulation and gaming to support training, military analysis and business strategy. Dr. Mastaglio served as the Executive Director of the Virginia Modeling, Analysis and Simulation Center at Old Dominion University from 1996 to 2000. Dr. Mastaglio is a 1969 graduate of the U.S. Military Academy. He retired from the Army in 1991 and has worked in the defense industry for IBM and Lockheed Martin. Dr. Mastaglio earned a Ph.D. from the University of Colorado in Computer Science in 1990. His research interests include using artificial intelligence to improving human-computer interaction and learning, cognitive modeling, developing large-scale enterprise models and simulations, and M&S educational requirements.

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INTRODUCTION

This paper and presentation overviews a joint effort between Orbital ATK (the user) and MYMIC Training (the developer) to demonstrate an augmented reality training system prototype to prepare workers in a virtual environment to execute an extremely hazardous task involving the manufacturing of rocket motors.. Our joint efforts leveraged previous investigations into immersive technology by Orbital ATK on ways to improve their training regime and efforts by MYMIC to explore commercially available technology that delivered virtual and augmented reality interactive solutions for training in general.

OVERVIEW OF TRAINING CHALLENGE

Orbital ATK is the world's largest manufacturer of solid rocket motors. Solid rocket motors are used for manned and unmanned space exploration, satellite deployment, missile defense systems, warfare armaments, and many other uses. Mixing and handling solid rocket fuel can be hazardous without proper procedures and training. Training new personnel or even keeping experienced personnel alert, attentive and vigilant can be challenging and costly. Since rocket fuel and its ingredients can be highly flammable and dangerous, training is generally limited. Training individuals on fuel handing, mixing and cleanup is not easily practiced using real or live ingredients. When live training is conducted, it is done using inert materials and off-line facilities.

Rocket fuel is typically mixed remotely in large batches of 50 to 1800 gallons. Several of these mixes are made and then transported to a casting facility where the fuel is poured into a rocket motor casing. The process can take hours or even days just to fabricate a single solid rocket motor. Remote operations limit an operator's hazard exposure time, but it does not eliminate it. While operator mistakes do not often result in death or injury, they usually result in the loss of tooling and facilities and have significant impact financially and negative consequences on business.

Because rehearsing or demonstrating accidental fuel spill cleanup with live ingredients would be too hazardous to include in a training exercise, other methods have been developed. One method of training personnel is called "air casting". During an "air cast" fabrications facilities are taken off line and the propellant mixing and transportation process is simulated without using any ingredients -- instead using only "air". While this process is instructive, it is also costly since it requires that personnel, production tooling and facilities be taken offline for two to three days at a time. An offline training exercise involves dozens of personnel, plus equipment and facilities costing hundreds of thousands or millions of dollars. A typical "air cast" training exercise can cost tens of thousands of dollars but still does not train personnel on potentially anomalous conditions and scenarios.

Another typical method of training new personnel is to have them "shadow" experienced workers during the actual fabrication and build process. This too has limitations and can be very expensive. Doubling personnel is costly and this approach requires months or years to bring personnel up to an experienced level. Even using this method, exposure to "what if" scenarios and potentially catastrophic incidents is limited.

TECHNOLOGY SELECTED AND USED

Early in 2015, Orbital ATK began evaluating Virtual Reality (VR) as an alternate approach for training personnel in rocket propellant mixing, casting and handling. The Propulsion Systems president and general manager is a former NASA Shuttle astronaut who challenged the engineering staff to look at VR technology, which he had been exposed to during his NASA shuttle mission training. Orbital ATK learned that NASA had been one of the early adopters of VR for training, but outside of some high-end flight simulators and military warfare training, VR technology had not been adopted systemically as a preferred training tool by industry. The high cost of VR systems and training scenario development may have limited its use to large government organizations such as NASA or the Department of Defense (DoD).

However, since the technology was evolving rapidly, the engineering staff pressed forward. The Orbital ATK team explored the VR Computer Assisted Virtual Environment (CAVE), 3D Power walls, Head Mounted Displays (HMD) and haptics as potential technologies that could be employed. They visited government and industry installations using and developing VR. Most sites had significant budgets, dedicated personnel and facilities with investments in the millions of dollars. The engineers at Orbital ATK built several prototypes using various simulation software and hardware. They focused on newly emerging consumer technologies and hardware with lower price points. The team felt the most promising technology to meet Orbital ATK training was the newly emerging low cost HMDs. The team eventually settled on the Oculus Rift HMD and the Unity 3D software gaming engine to develop a pilot project. They selected a few simple training scenarios and partnered with MYMIC Simulations to develop these training scenarios. "Industrial gaming" as it has been called, presented an intriguing possibility for Orbital ATK to develop VR training that could save money and better prepare operators for the hazards of mixing rocket propellants.

DEVELOPMENT APPROACH AND SYSTEM DESCRIPTION

Customer Requirement

Orbital ATK was exploring this training for use with employees in their organization who have limited experience or who need to train for anomalous or potentially hazardous conditions. Many of these technicians would have never experienced these conditions in a live mixing scenario. Mixing facilities have high demand and highly restricted access for safety and security purposes. Consequently, a virtual environment representing an existing mixing facility had to be built to accurately replicate an actual facility. The look and feel of the virtual mixing facility was a critical technical requirement. The goal was that once the trainee had experienced and practiced the training in the virtual world, they would work in the actual facility and be able to transfer the skills and knowledge gained in executing the virtual experience; they need to be fully aware of their surroundings because of that virtual experience. The MYMIC/Orbital ATK development team used the ADDIE model depicted in Figure 1 to design and build the interactive immersive training system.

Figure 1. ADDIE Model

Development of Training System

The analysis and design phases dictated a level 4 training system. Figure 2 distinguishes the differences between different training levels. Level 4 is the highest level of immersion and interactivity.

Figure 2. Levels and Associated Elements of Interactivity

CAD drawings, video footage and pictures taken from multiple directions were used to create the virtual representation of the Orbital ATK facility in the Unity version 5.3 game engine. The virtual world and user experience were designed to be as realistic as possible, using off-the-shelf commercially available technology to deliver an acceptable high-definition portrayal of the task environment and conditions under which it was to be performed.

Oculus Rift version Development Kit 2 was connected to the virtual world replicating the rocket fuel mixing facility. The Oculus Rift SDK is a comprehensive plug-in that was implemented in Unity to allow full interactivity between the two independent systems. Oculus comes with a predefined camera rig that allows the Rift to be used within Unity. The remainder of the connectivity was programmed using C #. Several avatars were created for use within the training system and could be changed as needed for the different scenarios that would be executed by the trainees. The avatars were created using the Autodesk character creator.

The Xbox 360 game controller system was included in our implementation to allow users to interact with the virtual environment using game control actions. The game controller permits the user to perform character movements and interact with objects represented in the virtual environment.

The image in Figure 3 shows the replicated mixing facility; note the level of fidelity achievable using commercial software. Our avatar, Nathan, is the instructor. The student is wearing the Oculus headset and is fully immersed in the virtual world of the facility as a first-person player (see inset picture of student below) as he interacts with Nathan using game controller actions.

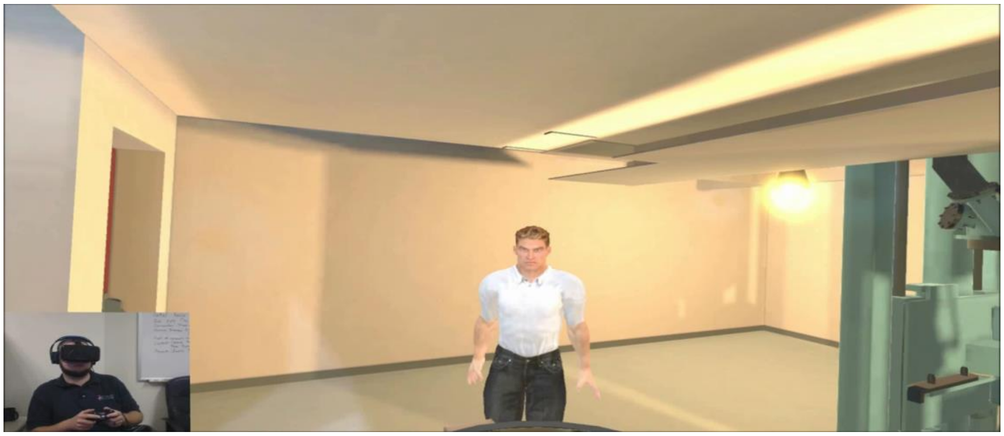

Figure 3. Avatar Nathan in the Mixing Facility

A critical technical requirement for the student is to be able to freely walk around in the facility, interact with all objects within the facility and carry out the instructions given by the Avatar representation of their instructor. The training objective in this scenario was the careful removal of Foreign Object Debris (FOD). The image in Figure 4 shows the "mixing bowl" where rocket propellant is made. The bowl contains an item of FOD that has to be removed by the student. In the fully virtual world, the mixing bowl can be moved back and forth on the rail tracks. The lid of the mixing bowl can be removed and its interior viewed. Once the propellant is mixed, the lid has to be closed and the bowl moved along the rails into the mixing area. As you can see in Figure 4, the mixing blades descend into the bowl once it is positioned below them by the trainee.

Figure 4. Mixing Bowl and Rails

Once the virtual world is built and connected to the Oculus system, multiple scenarios can be programmed. Orbital ATK could potentially use a VR system to train or certify technicians in order to better prepare them to work in an actual facility.

A major challenge with the implementation of this system was the speed of the camera movement. Because of the high level of fidelity and accuracy of the virtual world, image latency can occur in the headset, causing some users to experience motion sickness. This was mitigated by recalibrating camera angles and camera movement within the virtual world after user evaluation. Increased capability graphics cards were also shown to improve latency and mitigate motion sickness.

TESTING AND RESULTS

Virtual Reality is a proven tool for design, simulation and analysis. It has been used at companies like Caterpillar, Ford, and Lockheed-Martin for several years. However, more routine use for training is just emerging as a viable application for VR. In 2015, our research found only a few limited examples of industrial training using VR, many projects, even from defense organizations when closely examined were laboratory and experimental implementations used to collect data and not delivered and accepted systems. Ones identified used scenarios with potentially catastrophic outcomes (loss of life and/or loss of high cost equipment).

A propellant mixing building and mixing bowl inspection was selected as Orbital ATK's proof of concept because it is an inert operation and can be used to demonstrate the efficacy and acceptability of the technology. This scenario was selected as a simple demonstration of the technology to gauge technical feasibility, technician acceptance, training effectiveness and cost for implementation.

The pilot project created a very simple training scenario for the Oculus Rift HMD using MYMIC Simulations to script, develop and produce an “industrial game”. Much like a 2D video game, the scenario could be practiced over and over again. Technicians develop familiarity and skill each time they run the VR training simulation. The VR training followed a “see it”, “do it”, then “practice it” format. In the VR training, the trainee is instructed by an avatar then led through the inspection process. Trainees must listen and follow instructions to successfully complete the required exercises under situations that required handling distractions and interruptions in the prescribed process.

A mix bowl inspection requires that before propellant mixing begins, the mix bowl and associated tooling must be inspected for FOD. History has shown that FOD can be a source of ignition for a batch of rocket fuel being mixed. Catastrophic consequences can occur if FOD is not discovered and eliminated during the inspection. The mix bowl inspection included acknowledged and not so obvious sources of FOD. It also included process interruptions. Both of these have been historical sources for incidents. The inspection scenario demonstrates how a trainee might learn to deal with process interruptions and learn from past mistakes that have resulted in loss of life, equipment or rejected product. Several subtle FOD anomalies were also introduced in the scenario to see if trainees recognized them. In a completed training scenario, trainees would be scored on their ability to recognize and eliminate potential FOD issues.

The mix bowl inspection training pilot was reviewed by engineers, industrial training, management and technicians performing live propellant operations on the factory floor. The overall reaction and acceptance of VR training was very positive and quite well received by all groups. Some of the VR training observation results are as follows:

- VR provides better immersion and spatial familiarity with equipment and facilities than traditional training materials including 2D computer-based training. Technicians were generally very positive about VR training.

- It was observed that VR helps train and condition technicians to handle "what ifs", hazards, and prior known anomalous scenarios
- The realism and immersion of HMDs was superior to other VR technologies evaluated, including CAVEs, Power walls and augmented reality glasses.
- The repetition and realism of a VR experience may accelerate the process of developing experienced technicians. For example, one person who had never visited the actual propellant mixing building first became familiar with the building layout and tooling through the VR training. When this person physically visited the building for the first time, he reported that he was already more comfortable with the facility, tooling and process steps he had practiced in the VR training simulation than he would have been otherwise.
- There are several methods involving expensive equipment that can scan or model the buildings and tooling. We found, however, that we could model the building and tooling relatively inexpensively, since we already had CAD models of both and could easily convert them to compatible objects in Unity.
- Some level of VR sickness was experienced by about 20% of the participants using the Oculus Rift.
- VR sickness was attributed primarily to 2 factors: 1) *Display latency* of the early Oculus DK-2 headset. Current efforts using HTC VIVE hardware are much improved. In general it was discovered that display latency of 20 milliseconds or less is required to prevent VR sickness. 2) Unexpected motion caused the trainee to be "whisked" along by the simulation. We found that it is preferable to let trainees move around in the workspace on their own, rather than move them around the space automatically.
- Developing robust training can be costly and requires a level of gaming expertise that is not typically found in most companies. Much like developing a good video game, the storyboard, contingencies and objectives must be scripted and programmed into the training. If this expertise is not readily available, then a company or partner who specialized in VR training development can be a good investment. However, costs for developing VR training were about $3K per minute of training which could still be cost prohibitive for some organizations.
- CAD models and gaming software such as Unity are recommended for industrial training rather than expensive physics-based simulation software used for engineering analysis. Typical physics-based software, while good for understanding failures, provides and requires too much detail for industrial training.

The mix bowl inspection training pilot was tested and provided positive results. This effort concluded that VR provides a number of benefits that are difficult to train in real life yet provided the MYMIC/Orbital ATK team important insight into its use.

LESSONS LEARNED

This project resulted in several key observations and lessons learned that will be used by the participants in this development to guide future implementation of virtual reality based training. Some key lessons learned are listed below:

- Virtual reality based training development requires a specialized skillset that includes storyboarding, scripting, and video game level programming. Few companies have the expertise necessary to develop this internally. Partnering with a company who has this expertise was a good investment, even at rates of $3K per minute of training.
- High fidelity physics-based simulation software is good for engineering analysis and investigations, but proved much too detailed for virtual reality-based industrial training. Leveraging existing company developed CAD models together with gaming engine software such as Unity proved to be a good combination for virtual reality-based industrial training.

- The implementation of the Xbox 360 game controller with Oculus and Unity can be achieved successfully in order to afford a trainee using a VR headset to execute interactions within the virtual world. The development approach from this project was leveraged by MYMIC to reengineer other existing virtual environment-based training systems, such as a ship tour that supports the vessel familiarization required of all merchant mariners working aboard a ship.
- The motion sickness issue was resolved, but not fully eliminated by careful re-angling of cameras and changing camera speeds. Investment in more advanced, latency tolerant graphics cards also helped mitigate motion sickness effects.

CONCLUSION

This project demonstrated the efficacy and affordability of implementing virtual reality training to meet the needs of a commercial entity or an industrial user to train employees on critical dangerous tasks that cannot be replicated in a real world environment due to the hazards involved or cost. Standard commercial software and hardware can be used in a practical virtual reality training system that actually provides superior training to other more complex interactive technologies, such as the CAVE and Power walls, at significantly reduced costs. Industries, even those with organic training departments, will require for the foreseeable future the partnership of a training developer with expertise implementing and deploying virtual and other immersive technologies. Motion sickness continues to be an issue, one that varies amongst users, and must be one of the key assessment criteria so that design changes (such as camera angles and control of movement within the virtual environment) can be made to reduce it to an acceptable level. Virtual Reality based training has a future as a key technology that should be considered in those situations which require training of hazardous or costly tasks.

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