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CONFIGURING VIRTUAL REALITY DISPLAYS IN A MIXED-REALITY ENVIRONMENT FOR LVC TRAINING

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ABSTRACT

In order to adapt to an ever-changing set of threats, military forces need to find new methods of training. The prevalence of commercial game engines combined with virtual reality (VR) and mixed reality environments can prove beneficial to training. Live, virtual and constructive (LVC) training combines live people, virtual environments and simulated actors to create a better training environment. However, integrating virtual reality displays, software simulations and artificial weapons into a mixed reality environment poses numerous challenges. A mixed reality environment known as The Veldt was constructed to research these challenges. The Veldt consists of numerous independent displays, along with movable walls, doors and windows. This allows The Veldt to simulate numerous training scenarios. Several challenges were encountered in creating this system. Displays were precisely located using the tracking system, then configured using VR Juggler. The ideal viewpoint for each display was configured based on the expect location for users to be looking at it. Finally, the displays were accurately aligned to the virtual terrain model. This paper describes how the displays were configured in The Veldt, as well as how it was used for two training scenarios.

INTRODUCTION

As military forces around the world learn to adapt to a new and changing set of threats, their training techniques need to evolve. Existing training techniques, while still effective, can be supplemented with new methods that take advantage of current research in computer simulation, virtual reality and mixed reality environments.

Current techniques for military training include the use of classroom learning, live action simulations and firing ranges. Each of these has strengths and weaknesses, but utilizing them together helps mitigate the drawbacks to each method. Military forces have begun augmenting these training techniques with additional tools, such as game-based simulations or virtual firing ranges. [1] These newer tools offer trainers high-fidelity tracking of user performance and high repeatability of a given training scenario.

One game engine-based simulation that is widely used in the United States Army is Virtual Battlespace 2 (VBS2) [2]. With the ability to create realistic training scenarios, allow soldiers to operate vehicles and work in squads, VBS2 can simulate a wide variety of battlefield environments. A screenshot of VBS2 is shown in Figure 1. VBS2 also offers the ability to connect to other training

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applications and environments through standardized communications protocols such as High Level Architecture (HLA) [3] and Distributed Interactive Simulation (DIS) [4]. Through this capability, training simulators can be built using authentic weapons and vehicles. However, VBS2 has some limitations that reduce its ability to be used standalone for large-scale training environments. The main limitation is that VBS2 is designed to run on a single computer with one display. This prevents VBS2 from being used to drive the graphics in a large-scale VR system.

Figure 1: A military training simulation in VBS2.

Another newer type of training system is a virtual firing range. Companies such as LaserShot [5] or Meggitt Training Systems [6] produce training simulators that use modified authentic weapons that can be tracked during the simulation. Users interact with a training video that can take various branches based on trainee's behaviors. These simulators also offer after action review (AAR) [7] so trainers can review trainees' performance after each simulation. Like real firing ranges, trainees using a virtual firing range must remain stationary during the simulation—they can't move through a physical environment because the systems use a single projected display.

Virtual reality (VR) systems have grown and changed dramatically since their inception in the 1960s [8]. Today, virtual reality is widely used in academia and industry as a valuable tool for research [9], product design [10] and training [11]. As the number of applications for VR has grown, the capabilities of the display systems has also grown. While VR started by using a large, heavy and low resolution head-mounted display (HMD), current systems are capable of showing high resolution, realistic images [12]. These more immersive systems give users better situational awareness and offer a more realistic synthetic environment.

In addition to virtual reality, mixed reality environments have been the topic of new interest in recent years. Mixed reality is the combination of physical and virtual environments to create a unified environment for simulations [13]. These systems can include various types of display systems, physical barriers or obstacles, tracking systems and interactive components [14]. In particular, environments and simulations that necessitate a user's interaction with physical devices can benefit greatly from mixed reality environments.

BACKGROUND

In an effort to improve training systems, researchers and trainers are exploring the use of mixed reality environments. These systems take advantage of existing simulation software and display systems to create a more realistic and capable means of training soldiers. One challenge when using mixed reality environments for training is providing realistic weapons and scenarios. Another challenge is integrating live and virtual actors into a cohesive training environment. Creating a mixed reality environment for military training involves integrating simulation software, VR displays, tracking systems, simulated weapons and physical, reconfigurable walls.

LVC Training

The United States military is currently adopting Live, Virtual and Constructive (LVC) training systems for much of their training needs [15]. LVC training incorporates live people using real equipment *(live)*, live people in virtual environments *(virtual)* and simulated people, or actors *(constructive)*. This combination can offer more realistic and more complete training than any one component can offer alone. One of the key challenges in developing LVC training systems is interoperability between physical devices, computer simulations and computer graphics generators. With each of these components responsible for different parts of the overall environment, they need to communicate with each other effectively and accurately. To this end, the HLA and DIS protocols were standardized and implemented. These protocols allow independently developed tools to communicate status about actors and situational events. This interoperability is critical to the success of LVC training techniques.

A wide variety of commercial and research tools exist to support LVC training. Some commercial tools, such as VBS2 and OneSAF [16], are used to simulate synthetic entities, such as soldiers, enemy combatants and vehicles. These tools are key to the *constructive* component of LVC training. Specifically, VBS2 is commonly used to create scenarios that incorporate numerous virtual entities as well as live entities. In a training scenario, VBS2 is responsible for managing the events in the scenario and the artificial intelligence (AI) of the virtual entities. Additionally, VBS2 can be used to display the scenario in an interactive, 3D viewer. OneSAF is another tool for controlling the behavior of the virtual entities in a simulation.

In order to support *virtual* actors, or live people in a virtual environment, there is a need to incorporate simulated weapons into the training simulation. Simulated weapons need to be as realistic as possible, while remaining safe for training purposes. They also need to incorporate sensors so the simulation knows where they

are, where they are pointed and when they are fired. Additionally, the ability to simulate weapon jams and ammunition reloading can be beneficial. Real weapons that have been modified for training are available commercially [17], but are often quite expensive. A common alternative is to use airsoft weapons, which can be easily augmented to suit LVC training simulations [18]. In order to take advantage of these weapons, a simulated environment is necessary.

Virtual Reality Display Systems

One popular type of VR display system, the Cave Automatic Virtual Environment (CAVE) [19], is used to immerse a user in the virtual environment. By utilizing multiple walls with images projected from behind, users are surrounded by images, so that their forward and peripheral vision is used. This enhanced sense of immersion is one of the key benefits of CAVEs. However, this multi-wall configuration is also one of the drawbacks. It is often difficult to incorporate physical objects or barriers into a CAVE because of the limited space inside the walls. Finally, CAVEs are typically optimized for a single user, rather than multiple users simultaneously.

Often used on a smaller scale, single wall VR displays use a display surface with one or more projectors. These can be projected in either mono (2D) or stereo (3D). In addition to projected display surface, commercial TVs can also be used as a single wall VR display. Although single wall displays have a more restricted view into the virtual environment, they are less expensive and complex than a CAVE. Because of their small footprint, it's also easier to relocate a single wall display inside a room.

A key component of all VR display systems is the user's viewpoint. Although most VR systems are optimized for a single user's view, it is possible to incorporate multiple users' viewpoints into a single environment. By knowing where the primary user is located and where they are looking, the view on the display can be oriented that user's view of the environment more accurately, which results in the user feeling more immersed and part of the virtual environment. This is commonly accomplished through the use of a tracking system. Popular tracking systems include ultrasonic/inertial tracking, such as those from Intersense [20], or using markers and infrared (IR) cameras, such as those from ART GmbH [21].

The Veldt

In order to research and improve existing LVC training techniques, Iowa State University designed and built a mixed reality system known as The Veldt. This system incorporates physical and virtual devices, as well as multiple software components, to create a novel training environment. One of the key components in The Veldt are movable, reconfigurable walls, windows and doors. These pieces can be combined in a large number of configurations to create different training scenarios, such as a set of rooms, hallways or outdoor security checkpoints. A portion of The Veldt, configured as a room with a window, is shown in Figure 2. In addition to these walls, several simulated Jersey barriers were built for use in security checkpoint scenarios.

Figure 2: A portion of The Veldt configured as a room.

To incorporate the virtual aspect of LVC training, numerous single wall VR displays are used in The Veldt. These displays are a combination of rear projected displays and TVs. Some of the TVs are also capable of displaying stereo images. All of these systems can be easily moved independently of the walls to support different training scenarios. The configuration and use of the displays will be discussed further in the methodology section of this paper.

One requirement to building a mixed reality environment is the ability to track users and objects. To support this requirement, a Motion Analysis tracking system [22] was installed in The Veldt. This system uses twenty-four infrared cameras and retroreflective markers to identify and track objects in real-time. A helmet with retroreflective markers is shown in Figure 3. Motion Analysis's Cortex [23] application is responsible for controlling the tracking system and identifying objects. Cortex includes an API for transmitting tracking data to other applications.

Figure 3: A helmet with retroreflective markers

Several pieces of software are necessary for creating the training scenarios in The Veldt. The primary tool, VBS2, is responsible for creating the scenarios and controlling simulated entities. However, VBS2 has several display limitations that prevent it from being used effectively to display the simulation on the VR display systems. The main limitation is that VBS2 can only output on a single graphics pipe to a single display—it cannot be run on a computer cluster or in stereo. VBS2 doesn't support framelocking, where the graphics buffers are swapped simultaneously. Without this, an application can't run seamlessly on immediately adjacent displays. To address these limitations, an open source toolset known as DeltaJug [24] was created. DeltaJug combines Delta3D [25], a popular military training scenegraph and VR Juggler [26], an API used to create and control VR applications on a wide variety of display systems. By using DeltaJug, the graphics on all of the displays can be synchronized and shown in stereo. The application running in DeltaJug communicates with VBS2 via a stream of DIS packets that communicate the scenario state changes. A diagram of the software architecture of The Veldt is shown in Figure 4.
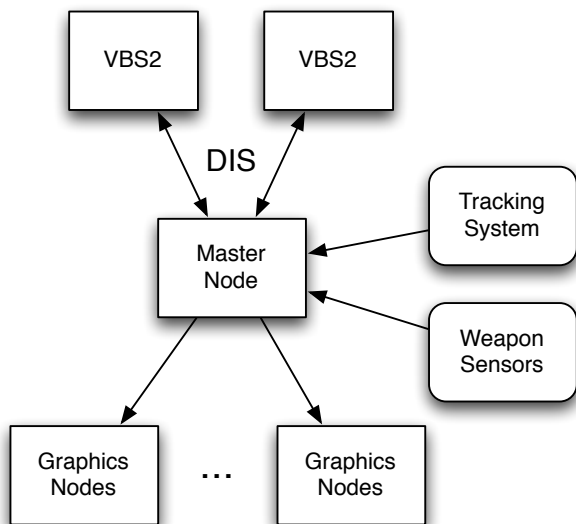

Figure 4: Software architecture of The Veldt

METHODOLOGY

In order to make The Veldt a viable system for LVC training, the display systems needed to be configured to fit into the intended training scenarios. For the initial two scenarios, five independent displays were used: two rear-projected screens, one LCD TV and two LaserVue TVs. Each display's graphics are generated by a dedicated computer, with a master node controlling the slave nodes. Reconfiguring The Veldt for a different scenario requires all of the displays, as well as the physical walls, to be moved and configured quickly. Switching scenarios is a common task, so this had to be accounted for when preparing the display systems.

A number of challenges arose when setting up the displays in The Veldt. The precise location of each display needed to be measured and recorded, then configured with VR Juggler. Because there is no primary user in The Veldt, a method for setting the viewpoint of each display was required. Finally, the displays needed to be accurately aligned with the virtual terrain and model of the environment.

Use of VR Juggler

As a part of DeltaJug, VR Juggler is a critical component in the display systems for The Veldt. Applications built with VR Juggler are able to abstract the display systems, input devices and computer configuration from the application. This allows an application to be written and compiled once, then run in a variety of environments. This is accomplished through the use of run-time configuration files that describe the computer cluster, displays and input devices. In The Veldt, VR Juggler allows the application to run and stay synchronized across all six computers and displays.

VR Juggler provides a means of framelocking independent computers via a TCP networking mechanism. When two or more displays are located immediately adjacent to each other, framelocking is critical to having smooth motion between the displays. Displays are also configured through VR Juggler, by defining the location of each corner of the display. This information is used to set up the view frustum and render settings for each display.

Laying out the displays

The first step in configuring the display systems for The Veldt was to determine where each display would be physically located. These positions were dependent on the layout of the walls for each scenario. To ensure consistency between reconfigurations, the floor was marked with the locations of each display and wall for each scenario. The locations of each display for one scenario is shown in Figure 5. With the locations set, the precise location of the corners of each display needed to be determined, relative to the origin of the tracking system.

Rather than attempt to accurately measure the distance to each display's corner with measure tape or traditional means, the tracking system was utilized. The Cortex software can display the location of an individual marker in the tracked volume with approximately 1mm precision. The calibration wand for the Motion Analysis tracking system is a precisely measured device that was easily and reliably tracked. The wand and Cortex's tracking ability was used to quickly and accurately locate each display's corner in The Veldt. Should the displays need to be relocated, or when another scenario is developed, this same technique be used to quickly
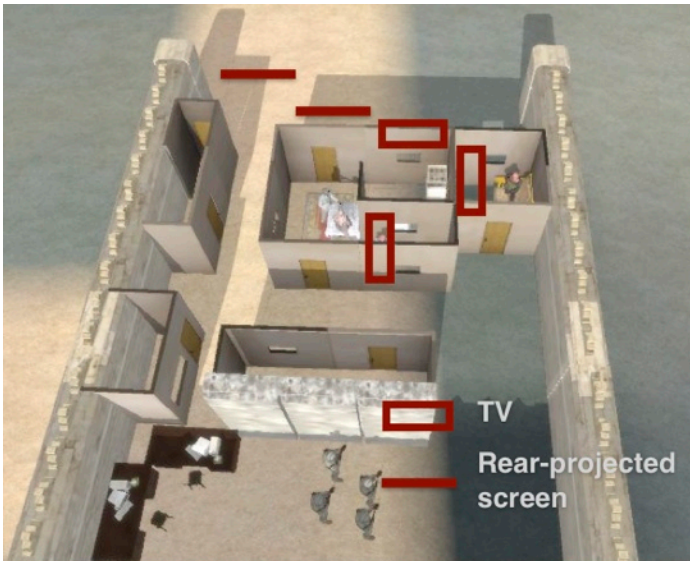
Figure 5: Display arrangement for the room clearing scenario in The Veldt

generate the required information for the new layout. This technique was critical in setting up The Veldt for each scenario accurately. Without precise measurements for each display, users aren't able to view or interact with the virtual world correctly.

Configuring the displays

VR Juggler was also used to set up the OpenGL viewports based on the physical location and dimensions of each display. Each display was described in the configuration file that is provided to VR Juggler when the application launches. A sample of the configuration for a display in The Veldt is shown in Figure 6. These configuration files are specific to each scenario and layout for The Veldt.

The `display_window` element was used to define the resolution of each display, the frame buffer configuration, stereo settings and other configuration options for the display. Every `display_window` element also contains one or more `surface_viewport` elements. The `surface_viewport` element was used to describe the location of each corner of the display, in meters. It also defines a `user` for each viewport, which controls the head position for each display.

Standardizing the viewpoints

In a typical VR display system, such as a CAVE, there is a single, tracked user. The primary user is normally tracked inside the environment, with the tracking system monitoring their position and orientation in real-time. With this information, VR Juggler is able to update the viewports and give the primary user a more immersive experience. However, this has a detrimental effect on any other users, because the display is only

```xml
<display_windows>
    <display_window name="LaserVue Left" version="6">
        <origin>0</origin>
        <origin>0</origin>
        <size>1920</size>
        <size>1080</size>
        <pipe>0</pipe>
        <frame_buffer_config>
            ...
        </frame_buffer_config>
        <stereo>false</stereo>
        <border>false</border>
        <hide_mouse>true</hide_mouse>
        <full_screen>true</full_screen>
        <always_on_top>true</always_on_top>
        <active>true</active>
        <surface_viewports>
            <surface_viewport name="Surface Viewport" version="3">
                <origin>0.0</origin>
                <origin>0.0</origin>
                <size>1.0</size>
                <size>1.0</size>
                <view>Left Eye</view>
                <lower_left_corner>-3.848</lower_left_corner>
                <lower_left_corner>1.007</lower_left_corner>
                <lower_left_corner>4.794</lower_left_corner>
                <lower_right_corner>-3.848</lower_right_corner>
                <lower_right_corner>1.007</lower_right_corner>
                <lower_right_corner>3.137</lower_right_corner>
                <upper_right_corner>-3.848</upper_right_corner>
                <upper_right_corner>1.94</upper_right_corner>
                <upper_right_corner>3.137</upper_right_corner>
                <upper_left_corner>-3.848</upper_left_corner>
                <upper_left_corner>1.94</upper_left_corner>
                <upper_left_corner>4.794</upper_left_corner>
                <user>CypressUser</user>
                <active>true</active>
                <tracked>false</tracked>
                <tracker_proxy />
                <auto_corner_update>0</auto_corner_update>
            </surface_viewport>
        </surface_viewports>
        <keyboard_mouse_device_name />
        <allow_mouse_locking>true</allow_mouse_locking>
        <lock_key>0</lock_key>
        <start_locked>false</start_locked>
        <sleep_time>75</sleep_time>
    </display_window>
</display_windows>
```

Figure 6: VR Juggler configuration for a display

optimized for the primary user's current position. This problem gets worse as other users are farther away from the primary user.

In The Veldt, there are always multiple users, so there is no primary user to track and optimize the displays for. However, the system can be configured and optimized for each scenario, with knowledge of where users are likely to be located when looking at a display. To take advantage of this information, each `surface_viewport` was configured with a separate VR Juggler `user`. Each `user` had a fixed position, rather than being attached to a tracked object as they would be in a typical VR environment. The fixed positions for each `user` were set in the most common location for a person to be looking at that display. This gave each display an ideal viewport, regardless of which user was looking at it. However,

users that weren't standing in the expected location won't have an optimized view.

Matching displays with the terrain

The last part of configuring The Veldt was aligning the physical walls and displays with their location in the virtual model. The virtual model contained the physical walls and displays, as well as surrounding buildings that created a more complete world. To ensure accuracy and consistency during training scenarios, the physical and virtual worlds needed to be precisely aligned on the terrain. The model of the environment used an accurate terrain model that corresponds to real-world locations.

The first step to aligning the physical walls with the virtual environment was to set the origin of the virtual model to match the origin of the tracking system. This placed the models in roughly the same location, but they weren't perfectly aligned. Because some of the VR displays were placed in the windows of buildings, these were beneficial in finalizing the alignment. Next, an offset translation was applied to the model so that all of the physical walls and displays were co-located with their virtual counterparts. Additionally, a rotation and scaling factor were applied to the model.

These steps were necessary for a couple reasons. First, the models weren't all created using the same units of measurement. Some models were in meters, others in feet. Second, VBS2 and DeltaJug have different coordinate systems that don't match on a 1:1 scale. The rotation and scaling factors were found experimentally to pair VBS2 coordinates with DeltaJug and real-world coordinates.

RESULTS

The unique set of VR displays and computers were successfully integrated into The Veldt in order to run a pair of training scenarios. The first training scenario involved a simulated room clearing, including an outdoor alley and set of hallways. The displays in this scenario were used to provide a view down the alley, out several windows and doors, as well as simulating an enemy combatant laying on the floor in the room to be cleared.

In the room clearing scenario, soldiers worked as a pair to move through a hallway and clear a pair of rooms. The first room they encountered had a breach door that was reinforced with a kick plate, to simulate a forced entry. Inside, a friendly non-combatant was sitting in a chair, with a virtual hostile laying on the floor. Through the window, additional hostiles may appear, depending on the variation of the scenario. A subsequent room could also contain friendly or hostile virtual actors. Figure 7 shows a rendering of The Veldt as configured for the room clearing scenario, with the expected path and breach door indicated. The starting location is shown at the bottom of the image and is represented by four soldiers.

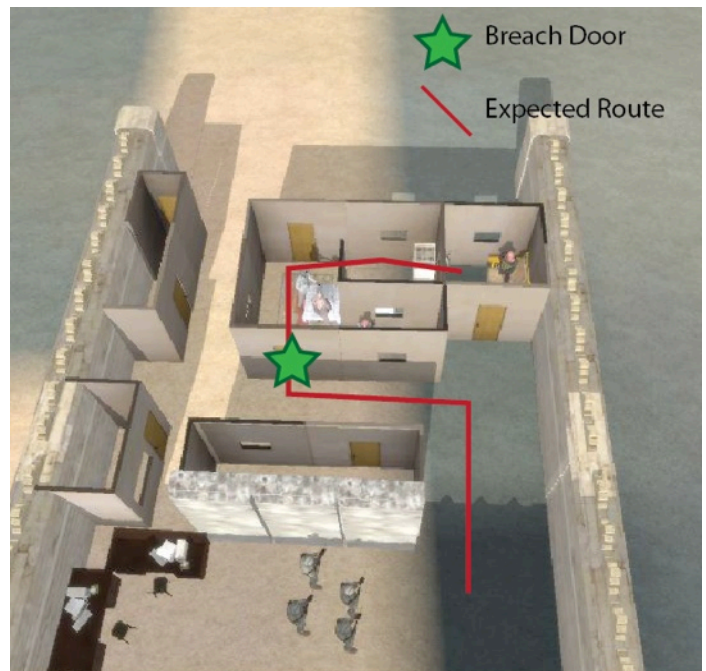The second scenario simulated a military checkpoint. This scenario used a pair of rear-projected displays to

Figure 7: The room clearing scenario in The Veldt

show the approach to the checkpoint, while other displays were used in the windows of surrounding buildings. Several movable Jersey barriers were used in this scenario, to increase realism and training fidelity. A view of the checkpoint scenario can be seen in Figure 8.

The checkpoint scenario presents soldiers with a number of events. Vehicles can approach down the road and come to the front of the checkpoint. These vehicles may contain friendly or hostile virtual entities. Also, the windows in surrounding buildings can display activity from the building's occupants. This may include hostile behavior or friendly occupants.

CONCLUSIONS & FUTURE WORK

This paper presented how a discrete set of displays was integrated and configured in The Veldt, a mixed-reality system to support LVC military training. DeltaJug, a combination of VR Juggler and Delta3D was created, then used to abstract the displays and computers from the software developer. To configure The Veldt, each display's location first needed to be precisely measured and marked. The display locations were measured using The Veldt's tracking system, which provided a fast, consistent and precise means of locating each display. These measurements were used in the display configurations for VR Juggler, with a different user defined for each display. This allows the display's viewpoint to be optimized for where the user is expected to be looking at the display. Finally, the physical walls and displays were precisely aligned with their virtual counterparts. A set of translation, rotation and scales transforms were necessary to match the coordinate systems between VBS2 and DeltaJug.
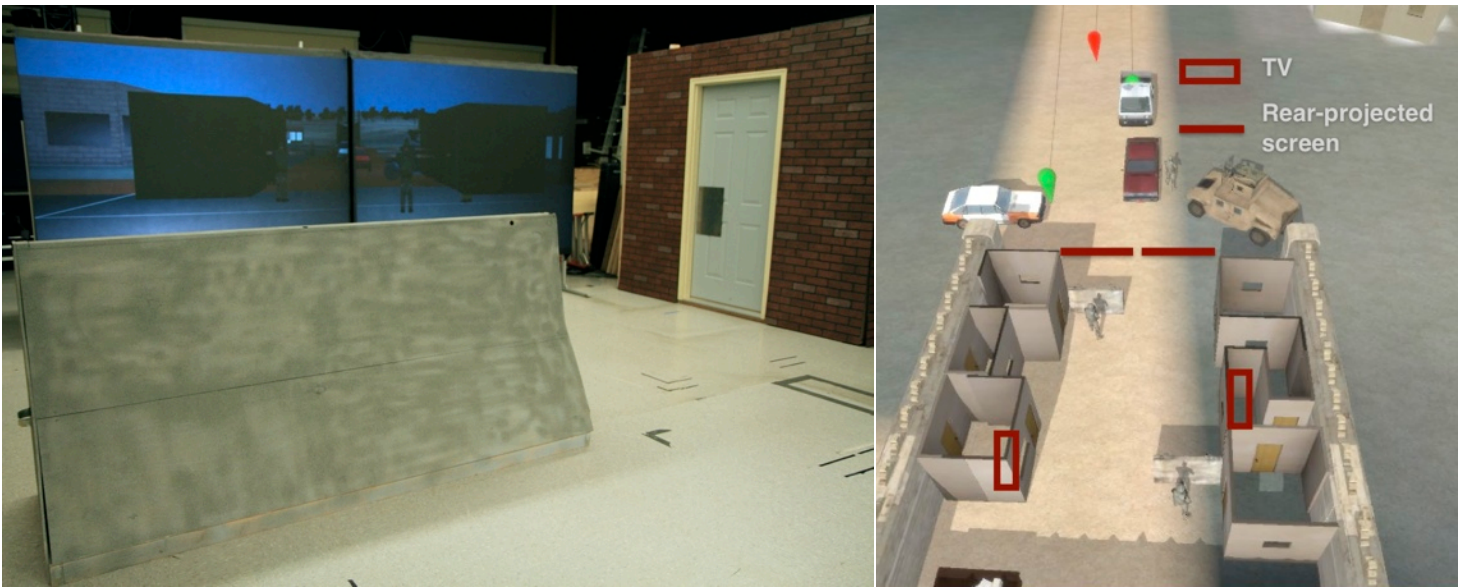
Figure 8: A photo of The Veldt arranged for the checkpoint scenario (left) and the display arrangement for the checkpoint scenario (right)

Additional work can be done to improve the display configuration in The Veldt. Data from the tracking system was used to locate the corners of each display for the initial setup. If the displays were tracked full-time, the system could easily tolerate irregular placement of the displays. Also, the viewpoints for each display could be improved through several different techniques. Each user is continually tracked in The Veldt. The viewpoint for each display could be changed in real-time to optimize the viewpoint for the user that is currently looking at the display. However, this may not work when several people are looking at the same display. In these situations, the group of user's tracking data could be averaged to create a nearly ideal viewpoint for the display.

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