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Graphics for Serious Games

RIST: Radiological Immersive Survey Training for two simultaneous users

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ABSTRACT

National Guard Civil Support Teams (CST) respond to a variety of situations involving dangerous materials. Many of these situations can be safely simulated for training purposes in the real world. Radiological threats, however, are difficult to simulate due to the lack of materials that can mimic radiation sources without the danger of the real radiation. To address the need for a system to train CSTs to respond to radiological threats, we have developed the Radiological Immersive Survey Training (RIST) system. RIST simulates radiological threats from multiple sources using a realistic real-time shielding model based on ray casting and allows users to practice surveying the threat using simulated representations of the world and equipment. We have developed an after action review tool to allow a trainer to show trainees a recording of their survey and how they can improve. We also created a scenario design tool to allow the trainer to create complex environments with radiological threats.

We developed novel multi-user interaction techniques to enable simultaneous training for two CST members in an immersive virtual environment. We also introduced a novel multi-perspective rendering technique for two users based on each user's task rather than field of view. Finally, we conducted a preliminary user study with several pairs of expert users to measure user preferences and the effects of using this technique, in conjunction with how altering which user navigated, on user performance. CST survey teams from two states have now used the system for training.

1. Introduction

Civil Support Teams (CST) survey chemical, biological, and radioactive threats in order to establish safe perimeters for the public and identify dangers. Training is critical to team member performance and safety while surveying a hazard. Training for CST tasks is a complex, coordinated team effort, and hazards, particularly radioactive, are currently difficult to safely simulate using traditional methods. Tate et al. have shown that training and mission rehearsal can benefit from virtual reality (VR) [1]. In particular, their research demonstrated that immersive systems can help users learn to perform visual and spatial tasks. Additionally, Chua et al. have shown that VR is effective for training to practice motor skills and perform movements [2]. We based large portions of our system's functionality and interface on communications with several members of a CST [3].

Radiological surveys typically involve a team of two CST members who survey an area to identify radiation sources. The teams survey inward toward suspected sources from up to eight directions. Perimeters of increasing levels of danger are indicated by placing colored flags at specific radiation readings. Fig. 1 shows a survey team forming such perimeters. The team will use more complex surveying patterns in complex areas where approaching from many directions is not possible.

Several existing training methods attempt to simulate this process. One method relies on survey meters that present preprogrammed radiation readings based on GPS location. Unfortunately, GPS readings are not sufficiently accurate for the task. Readings often fluctuate, providing inconsistent values. Another method requires a third person to consult a chart to determine the radiation reading the team should be observing at their current location. Inconsistency and inaccuracy are also problems with this method, as the third person can make mistakes while consulting the chart and must approximate the readings based on the team's location. In a similar method, the team reads radiation readings from cards placed on the ground.

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Fig. 1. CST members demonstrate a survey. (Left) The first surveyor signals for a flag and (Center) places it in the ground. (Right) The final flag arrangement with lines circled for emphasis.

While this eliminates some of the inaccuracy of a GPS device or chart reader, the pattern of the card locations generally hints to the location of the source. Finally, a live radiation field with real radioactive sources serves as a lesson on radiation and shielding for many first-responders and CST members. This could be adapted into a survey training exercise, but radiation exposure would limit the repeatability Surveyors' accumulated radiation exposures are monitored, and if members reach their annual limit, the risk of overexposure prevents them from responding in a real situation. Also, radiation cleanup is costly.

VR training can alleviate exposure concerns, improve the accuracy and consistency of the simulation, be easily repeated, and have minimal set up time. In general, use of VR has been shown to be effective in training for stressful situations. Its use can elicitemotional responses similar to those from real experiences, thus enhancing the CST's preparedness to perform in real-world stressful situations [4].

We present *Radiological Immersive Survey Training (RIST)*, an immersive virtual training environment for National Guard CST units. By simulating an event in an immersive virtual environment (IVE), we allow the team's movements to be tracked accurately and provide precise and consistent radiation readings based on a realistic shielding model, which simulates the way materials reduce radiation transmission. This model is used by our Virtual Survey Tool (VST), our Scenario Design Tool (SDT), and our After Action Review Tool (AART).

We simulate CST surveyor equipment and use a multi-perspective rendering technique to allow two users to train simultaneously. We conducted a user study to measure the effects of this technique, as well as varying which user navigates, on user performance. Despite a few drawbacks, our method allowed surveyors to complete their tasks more easily than when everything was rendered to a single user's perspective.

We also held two training exercises. The first involved eight members of a CST. The second involved four members of this same team, plus four members of a different CST. These exercises provided training to CST members who used the system and also provided us with feedback from expert users on the training value of the system. The first exercise included the user study while the second provided us with additional data about the effects of navigation on performance.

2. Related work

Many VR applications exist for training users in a number of safety-related procedures. A notable feature of our system is the ability for both members of a survey team to work together in the virtual world, whereas many of the previous applications were designed to train a single person. This apparent deficiency may have resulted from equipment constraints.

2.1. Virtual reality training

In 1997, Tate et al. developed a shipboard fire trainer [1] to help firefighters familiarize themselves with a large ship and safely practice fighting simulated fire. It used a single, tracked head-mounted display with a tracked joystick for navigation.

Then, in 2002, the Virtual Emergency Response Training System (VERTS) was developed as a training system in which a CST can practice responding to nuclear, biological and chemical threats [5]. Little information is available about VERTS, except that it was capable of running on a desktop system or with a large rear projection screen and allowed users to rehearse searching areas to locate dangerous materials, take samples, place alarms, and report to an off-site commander [6]. The system used head-tracking, possibly for use with after action review [7]. Both RIST and VERTS were designed for a pair of trainees to work together, but RIST includes many features not available in VERTS, such as perspective and stereoscopic rendering. Also, RIST displays realistic representations of the CST instruments, whereas the available VERTS documentation does not indicate the provision of realistic instruments. Using a tracked wand, RIST enables measurements to be taken realistically by physically moving a probe around the environment. VERTS is described as only tracking the head, thus preventing realistic probing of the virtual environment.

A CAVE-based application developed in 2004 trained military guards to stand watch at a vehicle checkpoint, using voice recognition to speak to animated drivers and head tracked perspective rendering to inspect suspicious vehicles [8].Support for multiple users was not required. In 2007, another system trained oil rig workers to properly respond to a fire [9].It used a stereoscopic desktop display, but did not support head tracked perspective rendering or multiple users.

In our previous work (Koepnick et al. [10]) we developed a CAVE^{TM}-based two-user CST survey trainer. Our system works on a 6-sided CAVE-like display and has a shielding model, recording system, multi-perspective rendering, scenario design tools, additional survey tools, and more general user-object interaction. We also conducted a user study.

2.2. Multi-perspective rendering

Other systems allowed multiple users to interact in the same virtual space. In the PIT [11], two users viewed screens across a shared volume while seated 90 degrees to each other. Head-tracked stereo rendering allowed each user to view a 3D model that appeared in the shared volume. Because the interaction space is limited to the intersection of the two users' viewing frusta, the data must fit into a relatively small area.

Another example of multi-perspective rendering in VRenabled co-located collaboration between multiple users in a CAVE by drawing picking rays from each individual's viewpoint [12]. This method renders the rest of the environment from a static viewpoint to eliminate unexpected distortion caused by another user's head motion. RIST uses a similar approach, drawing each user's tools to their perspective, but also draws the rest of the world to one user's perspective.

The duo-view system at EVL supported two pairs of shutter glasses, with the display sequencing over four separate views for the four eyes of the two users [13]. Combining shutter glasses with light polarization also allows multiple independent views [14]. These technologies are not available on the VR system used to develop RIST.

Another method used image blending and view clustering to create a composite of independently rendered views based on view-vector incidence angles [15]. This method distributed projection error between viewers when they view similar areas. Our method gives each user an appropriate view of the elements of the scene necessary for that user's tasks.

Other researchers have studied the effects of perspective rendering on users' task performance. Arsenault and Ware [16] found that stereoscopic rendering was more important than correct perspective rendering for visually guided tasks, although correct perspective rendering did measurably improve performance. While our approach can provide a suboptimal view for each user, it at least provides a correct perspective rendering of the relevant objects needed for each user to complete their task.

Our scenario design tool also builds upon past experiences in virtual reality application design. The design of radiological survey scenarios through the population of the virtual world is itself performed in VR. This bears some similarity to a design method for architectural massing [17] that allows users to use a table prop to manipulate architectural elements.

Replay of past recordings of virtual environments within other virtual environments was implemented in the MASSIVE-3 Collaborative Virtual Environment [18]. The "temporal link" mechanism was used for capturing and replaying a variety of activities including user movements, interactions with virtual objects, and speech. Though our after action review system does not capture speech, it does provide functionality similar to the rest of the "temporal link" system. It is specifically tailored to meet the needs of CST members, presenting information vital to the review of a virtual radiological survey.

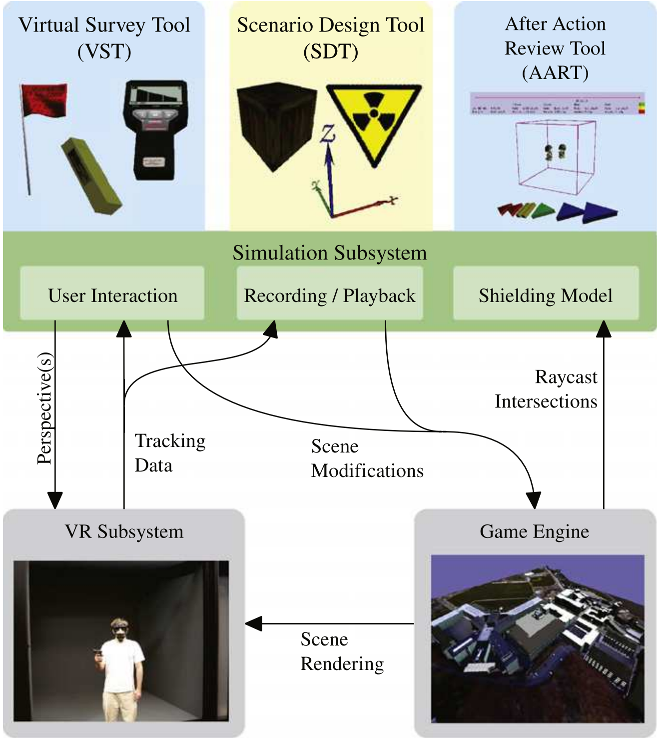

Fig. 2. All RIST tools are built upon the same simulation subsystem, which relies on a VR library and a game engine to handle perspective rendering and scene management, respectively.

3. Simulation system

We built our simulation upon Delta3D [19] and FreeVR [20]. Delta3D, an open source game engine that uses OpenGL, supports character animation, physics simulation, and compatibility with many major model formats. Making the engine work as an IVE required some effort. Combined with FreeVR, an open source VR integration library, Delta3D can work as an IVE with FreeVR handling the hardware interface, stereoscopic rendering, perspective correction, and other important VR tasks. An in-house VR library, Hydra [21], was used to add support for a cluster-driven 6-sided CAVE-like display. Combining Delta3D with these systems allowed it to work in VR environments, giving us a strong foundation upon which to build our training simulation. Fig. 2 shows the basic architecture of the system. Because Delta3D relies on the OpenSceneGraph library to handle the underlying graphics, we were fortunate to be able to build upon existing work to interface it with FreeVR [22] and Hydra. We developed this system for both 4-sided and 6-sided CAVE-style VR displays. The 4-sided CAVE immerses users with four 1048 × 1048 resolution projection screens that form three walls and a floor. The 6-sided system has projection screens that form four walls, a floor, and a ceiling, each with 1920 × 1920 resolution. In either system, two users each wear LCD shutter glasses to separate a synchronized stereoscopic pair of images, enhancing the experience of the three dimensional environment. Each user also holds a wand, a tracked six degree-of-freedom (6-DOF) input device with a hat switch, trigger, and several buttons.

3.1. Multi-perspective rendering

Very few VR systems support head tracked stereoscopic rendering for multiple users at the same time.The VR systems on which this application was developed do not support this feature, as it adds substantial cost and complexity. As a result, only one user of the simulation would see a correct rendering of the world while the other saw a distorted view, called the *satellite view*. When two users' head positions are close to one another, rendering to one user's *tracked* position results in minimal distortion for the satellite view of the other user.One strategy for dealing with this distortion is to render based on the average of the two head locations. In theory, this could result in less severe distortion across users. However, using the average position technique has the significant drawback that movement of either user will generate movement in the rendering for both users, which will generally disorient the non-moving user [12].

Our first approach was to render everything from the first user's perspective. We felt that in our simulation, the view of the first user, who usually stands in front, was more important, since he needs to be able to easily read the measurements of his virtual equipment and perform more direct interaction with the environment than the second user. During preliminary testing, we observed that the second user had difficulty using and reading his tools because those tools were rendered based on the first user's head position.

To mitigate the perspective problems facing the second users, we developed a multi-perspective rendering technique that can render objects for different perspectives. Based on each user's role and tasks, we decide which user would benefit most from seeing the correct perspective for each object, and assign that user's ID to the object. The world without any tools is rendered to one user's perspective. Then, for each user, the tools that are needed by that user are rendered to their perspective. We compute a perspective transformation for each user and push this transformation onto the OpenGL stack. The scene is rendered from each user's perspective, culling all objects that do not match that user's ID. When one user passes an object to the other user, it will be rendered from the sender's position until the receiver presses the trigger to acquire it, at which point the perspective for the object shifts to the latter user. Fig. 3 shows a comparison of each user's view as the distance between the users varies.

While this technique allows each user's tools to be rendered to their perspective, there are notable drawbacks. First, the depth information stored within the graphics z-buffer before rendering

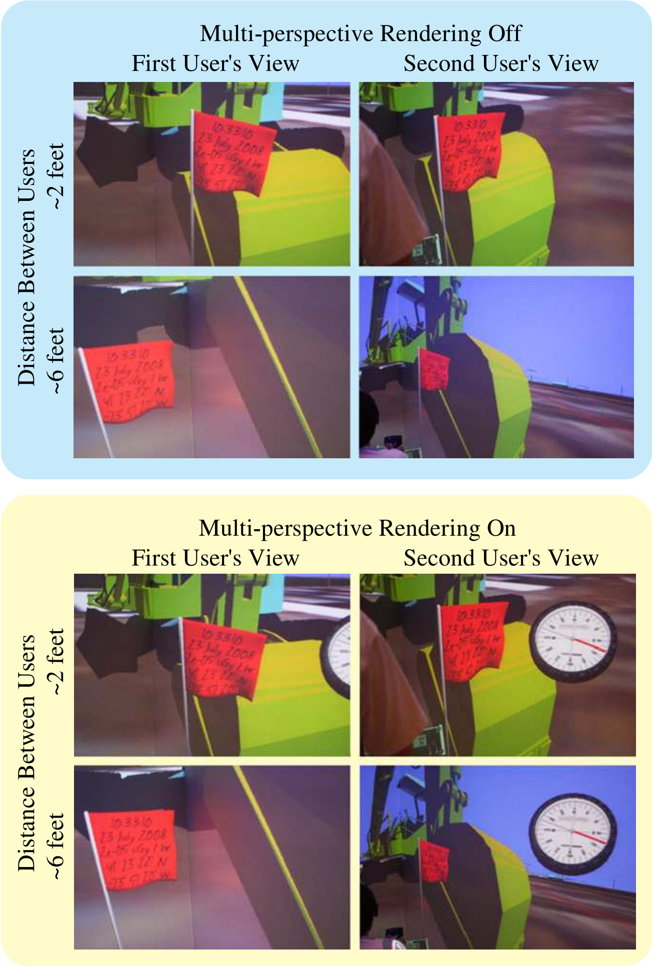

Fig. 3. Views of each user under different rendering conditions illustrate the impact of distance between users and show the benefit of multi-perspective rendering for the second user to use his equipment.

for some user was generated using some previous user's perspective. As a result, errors in depth testing can occur; the stored depth values have no relation to the depth values of newly rendered fragments. Rendering a new depth buffer for the current user presents a similar problem since the new depth values have no relation to the color fragments rendered for the previous user. Currently, the system maintains the depth buffer from the previous rendering pass. Another potential problem with this technique can result from user behavior. If a user orients his tool such that it is rendered within another user's field of view, the other user will see a distorted tool. Based on our observations, this can be particularly distracting if one user's tools are rendered over another user's tools, but this is an infrequent occurrence that is easily overcome.

3.2. *Object manipulation*

Either user can grab and move any movable object by moving the wand near it and pressing the trigger, whereupon the object undergoes the same transformations in location and orientation as the wand. Pressing the trigger again allows them to drop the object. If one user is holding an object, the other user can take it in the same manner as a static object. The user holding the object loses it when the other user grabs it. This is a natural technique for passing objects, for example the flags as shown in Fig. 4, between users [10].

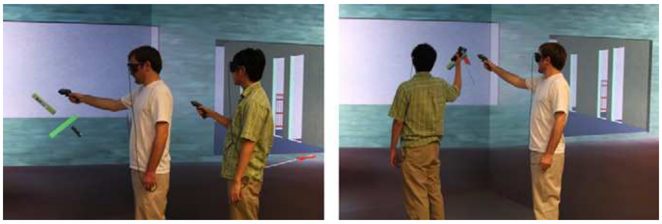

Fig. 4. (Left) Users demonstrate the system in a CAVE. (Right) The second user passes a flag to the first user.

3.3. *Navigation*

Either user can make the pair travel by pressing his hat switch in any direction. The users can decide which user will navigate, and can even navigate at the same time. In this case, the system averages the two inputs. In the 4-sided CAVE, users can turn in the world by pressing the hat switch to the side. With only three walls, this is necessary in order for users to see what is behind them. Sidestepping in this IVE can be a difficult maneuver that requires pointing the wand to the side and pressing "forward" on the hat switch. The 6-sided system fully encloses users, so rotation using the hat switch was removed. Instead, a user physically turns his body, as in the real world. With rotation disabled, pressing to the side on the hat switch allows the user to sidestep.

Collision detection and response pose challenges in IVEs. If the user physically moves and collides with a virtual object that should stop him, we are unable to restrict the user's physical movement in the real world. Our solution, therefore, is to move the world away from the user. This creates an effect where a user can walk into a fixed object and push it away from him by moving toward it. This ensures that the user's virtual position remains constant regardless of his real world position.

In order to simplify the collision response system, we chose to only allow the first user, who typically performs more detailed interactions, to collide with the world. It would be possible to create collision responses for both users, but this could create unresolvable collision configurations if, for example, both users approached an object from opposite sides. Because one user's view of the world is distorted, we felt this user's collisions would be confusing, but we have not studied this.

Appropriate collision response requires some assumptions about the users' positions in certain situations. Because we do not know the position of the user's feet, we assume they are directly below the glasses. If a user tries to lean over an object, whether or not their feet actually move, we assume that the user has moved their feet into the object. We then determine whether moving the user onto an object would be too high for a single step. The user may step onto an object if its height is less than half the measured height of the glasses, which we chose to approximate the maximum height the user's feet are likely to reach. Otherwise, the user is impeded by the object.

3.4. *Recording*

In order to allow a team's survey to be reviewed, a recording system was implemented. We record the motion of any objects, including wands and glasses, whose locations or orientations change sufficiently within the virtual world, as well as button press events and the creation and destruction of dynamic objects such as flags. During replay or loading, events are triggered to cause the same action to occur again.

3.5. Shielding

Shielding is essentially the degree to which a material reduces the transmission of radiation. The shielding provided by a material is characterized by its mass attenuation coefficient, which we store in a database based on a material identification number. These material IDs are encoded in the material properties of each polygon in the scene. We have many materials in the database, such as concrete, glass, air, steel, and wood. The material properties also encode the thickness of any geometry that deliberately does not include an accompanying back face or can be considered hollow, such as leaves or windows represented by single polygons or empty boxes. To simulate shielding effects with point sources of radiation, we perform a raycast from the location of the source to the location where the measurement is taken as shown in Fig. 5. To classify segments of the ray as inside or outside of a volume of material, the normals of the intersected polygons are tested. If the dot product of the normal and the ray is negative, the ray is entering a new material. Conversely, if the dot product is positive, the ray is exiting the current material. If the coefficients at the entry and exit points do not match, the volume is assumed be equally composed of the two materials, so the average of the two coefficients is used. The length of the ray segment inside a material gives the thickness t of the material along the path of radiation to the measurement device. The intensity I_b of gamma irradiation exiting a material along a ray that enters that material is a fraction of the intensity I_a of gamma irradiation entering the material, attenuated by the material according to its mass attenuation coefficient μ/ρ, linear density ρ and thickness t, according to the following equation [23]:

$$I_b = I_a * e^{-(\mu/\rho)\rho t} \tag{1}$$

We do not simplify the equation further because each mass attenuation coefficient is available as μ/ρ. This attenuation effect is repeated for each segment of material that the ray passes through between the radiation source and measurement location. Note that air is also a material, but it has a very low mass attenuation coefficient. Mass attenuation coefficients and linear densities for all materials were obtained from an ANSI standard [24]. This method was developed to handle nested geometry, such as a shape representing an engine block inside a hollow shell of a car. However, errors can occur in geometry that is not water tight. If a ray passes through a gap in a model and never encounters the back face of the volume, the ray is considered to be inside of that material until the next polygon is hit, or the ray terminates. This can occasionally result in incorrect radiation readings, but the reading is often only momentarily affected. This shielding approximation also does not take into account the buildup factor of each material, which is defined as the ratio of the total value of a specified radiation quantity at any point to the contribution to that value from radiation reaching the point without having undergone a collision [24]. The raycast only computes the amount of radiation that passes through the material uncollided. The shielding reflects the amount of radiation that collides; our simulation does not allow this collided radiation to continue propagating through the material. Buildup factors are typically used to model collided radiation eventually reaching a destination after multiple collisions, but these contributions are small. While this is necessary for some applications requiring greater accuracy such as radiation shield design, its absence in RIST should not affect users' overall experience. What is important is that users perceive variations in the level of shielding in the virtual world depending on material types and thicknesses.

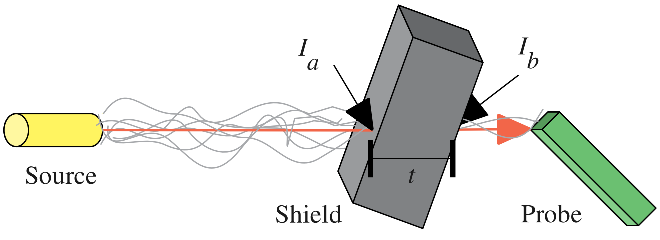

Fig. 5. The intensity of radiation exiting a material I_b depends on the thickness t of the shield and properties of the material as well as the intensity of the radiation at the point of entry I_a.

3.6. Radiation visualization

In order to assist users in understanding the effects of shielding, we created a radiation visualizer, shown in Fig. 6, which draws the radiation as a particle system. Each particle represents a gamma wave, and is rendered as a line emanating from the radiation source, moving away from it over time. To indicate shielding effects, the color of each line changes as it reaches various levels of radiation. We place a colored point at the location on the line where each important radiation level occurs. These colors directly correspond to the colors of the flags that the CST members use. Thus, the visualizer presents something similar to an isosurface at each important radiation level, but in the form of a point cloud. Once a line reaches its final point, indicative of the level where a green flag should be placed, it stops moving any farther, the other end of the line eventually catches up to this point, and the line disappears.

The visualizer employs the shielding calculations discussed in Section 3.5. To reduce the number of raycasts needed, each particle's raycast is performed only once. A ray is cast from the source of the radiation in a randomly determined direction, and all hit points are recorded. Later, when the particle is moving away from the source, these points are used to determine the appropriate color for the tip of the line. In order to improve the performance of the particle system, we do not sample the reading at every pixel of the line. Instead, we sample discrete points along the line and use hardware accelerated linear interpolation to color between the points. All of the ray's intersections with the world

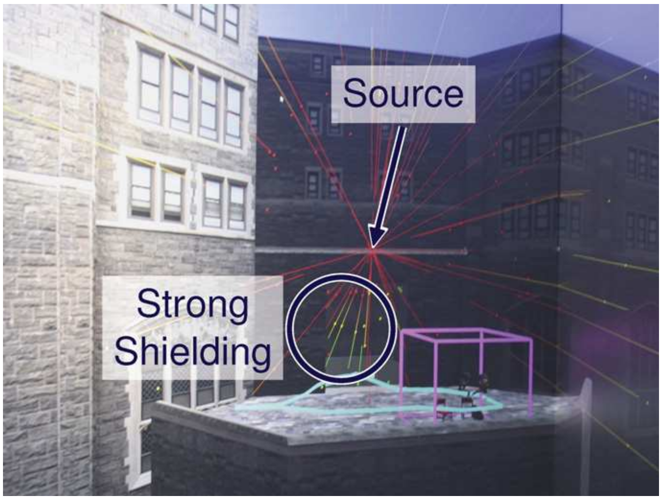

Fig. 6. The radiation visualizer displays particles indicating radiation levels. Particles emit in all directions from the radiation source on a ledge above the balcony door. Note the strongly shielded area, just inside the building.

are also in the list of points between which to interpolate. The color of the line at each of the sample points is correct; it is the transition between them that is approximated by interpolation. The number of samples is determined by the line's velocity, with a new sample point added every update at the line's tip. Since it is only the significant radiation levels that the users are actually concerned with, we feel that slight numerical errors are not detrimental.

4. Virtual survey tools

In an effort to recreate the experience of performing radiological surveys and improve training value, we have virtual versions of many of the tools the survey team uses in a real survey. Trainees use real gas masks with the lenses replaced with shutter glasses. Each survey team member is provided with a virtual belt located below the tracked head position, at approximately half the height of the head. When either user's wand comes into range of the belt, the objects contained in it appear and can be manipulated in the same way as any other dynamic object in the environment. Objects from the environment can also be placed onto either belt by either wand. Fig. 7 indicates the recommended way in which virtual equipment is controlled using hardware available in the VR systems. This arrangement is not required, as the users can choose what equipment they want at the beginning of the exercise.

The *AN/VDR-2* is used by the first surveyor to measure radiation levels. It consists of a readout unit with an attached handheld probe. The device is hung around the first surveyor's neck, requiring the operator to look down at it. In our virtual version, the readout unit can be positioned in front of the user's glasses, and the probe is attached to the user's wand. This was based on recommendations from CST members upon initial testing. All radiation measurement equipment displays radiation values based on the location of the equipment and the shielding model discussed in Section 3.5. The AN/VDR-2 can be grabbed and placed in the world; when it is grabbed again and released close to the user, it snaps back into position in front of the user.

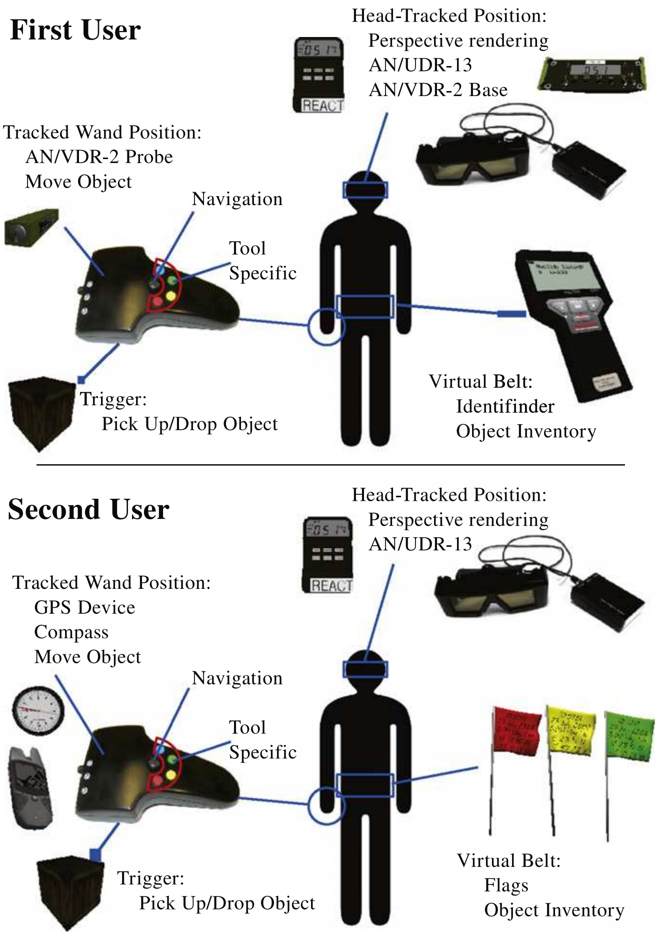

Fig. 7. User interface mapping of hardware devices to virtual survey equipment specific to each user.

The *AN/UDR-13* is a personal dosimeter worn by each survey team member. Each dosimeter records its wearer's accumulated radiation dosage and monitors the current radiation level. If the surveyor's accumulated dose or current dose exceed a set limit, an alarm in the dosimeter sounds. Normally, the dosimeter is worn on the chest, facing away from the user, and the user can look down to read it. In our simulation, however, each user's AN/UDR-13 can be placed directly in front of the user, facing him. We based this approach on feedback from CST members, who felt this worked more easily than trying to place the device very close to their virtual position and angle it up so it could be read. The AN/UDR-13 can produce both visible and audible alarms to indicate when a user's exposure limit has been exceeded, but our virtual AN/UDR-13 produces only a visual alarm. Like the AN/VDR-2, the AN/UDR-13 can be grabbed and placed in the world; when it is grabbed again and released close to the user, it snaps back into position.

The *Identifinder* is used to identify the isotope of a source if the strength of the radiation is within a certain range. During a survey, the first surveyor typically activates this device and sets it down to collect measurements. Both members then retreat to a location that lowers their exposure while the device operates. Once the identification is complete, they then retrieve the device. In our simulation, the menu system of the Identifinder has been replicated, and the three context-sensitive buttons of the device map to three buttons on the wand. The device can provide a graph of recent readings, which can be of use in observing shielding effects. Users can operate this device in a similar fashion to the real device and place it in the environment.

Colored flags containing important information about the time, location, and level of danger are placed in the environment by the first surveyor. The second surveyor carries these flags and writes the information on them with a permanent marker. In our simulation, the second user's belt contains flags of different colors, which he can grab to create a new flag. The system automatically writes the time, date, current AN/VDR-2 radiation reading, and GPS coordinates on the flag.

A GPS device and compass are carried by the second surveyor, who uses them to orient the team and track the GPS coordinates to write on the flags. In our system, we recommend that the GPS device and compass are placed on the second user's wand. Currently, the user cannot perform any operations on the GPS device, such as panning or zooming the map, so the map pans and rotates automatically to follow the team's movements.

5. Scenario design

Training scenarios can be constructed using the Scenario Design Tool. Built upon the same framework as the Virtual Survey Tool (VST), the SDT allows a user to design and validate a scenario inside the IVE. Incorporating the tool into an IVE presents two distinct advantages: the scenario can be viewed as a trainee would see it, and objects can be placed intuitively and precisely by a user with little experience with 3D modeling packages.

Upon initially loading the tool, the user is presented with a base version of the world with no interactive objects. The user can

Fig. 8. (Left) A user measuring radiation exposure in the Scenario Design Tool. (Right) A user selecting a tool within the Construct.

also load a previously saved scenario or a recorded training session and begin editing from that state. To facilitate quicker navigation and the ability to place objects, particularly radiation sources, inside of other objects, gravity and collision detection are both disabled. All actions that the SDT user is allowed to perform can be accessed within a secondary world called the "Construct." By pressing a button, the color of the scenario environment is muted and the Construct is rendered over it as shown in Fig. 8. The Construct contains objects that can be placed in the world. Upon selection, an object is bound to the wand and the user is transported back into the scenario world.

The most common Construct tools for populating the world with objects are model generators. Within the Construct, these tools appear as the model that would be placed into the world. When selected, a wireframe representation of the model is bound to the wand. The user can then orient the model and create the object in the scenario world. After exiting the Construct without a tool, the user can pick up and reposition any object that was placed. Entering the Construct destroys any held object.

The radiation tool lets the designer place and manipulate radioactive sources. While this tool is bound, lines from the wand to each existing source are presented, allowing the designer to observe which surfaces provide shielding against any source. The total exposure from all sources is displayed on the tool along with the type and strength of the selected source.

The designer designates the scenario's starting position by placing a marker in the environment. The designer can also teleport back to this position during the design process.

The models, radiation sources, and starting location are saved to a file as a set of model creation, source creation, and teleportation events, respectively, that are processed before the beginning of the simulation. As a result, a scenario can be loaded by enqueueing the events into the recording system during an actual training exercise, resulting in the events being triggered as part of the loading process. When the exercise is recorded, the scenario is recorded back into the file as well, allowing for complete reconstruction of the exercise at a later time without needing the original scenario file.

6. After action review tool

Training exercises can be reviewed in the IVE using the After Action Review Tool. The AART is designed to be used by an expert CST member to show trainees their recorded actions and how they can improve.

Upon loading, the users are presented with the world as it was at the beginning of the recording. Rendered at the top of each screen of the display is a Heads Up Display (HUD) showing a timeline of the recording, as seen in Fig. 9. Above the timeline are flag icons, appearing at the times when the team created flags. Below the timeline are the states of all of the team's measurement devices, including all accumulated and dose rate readings.

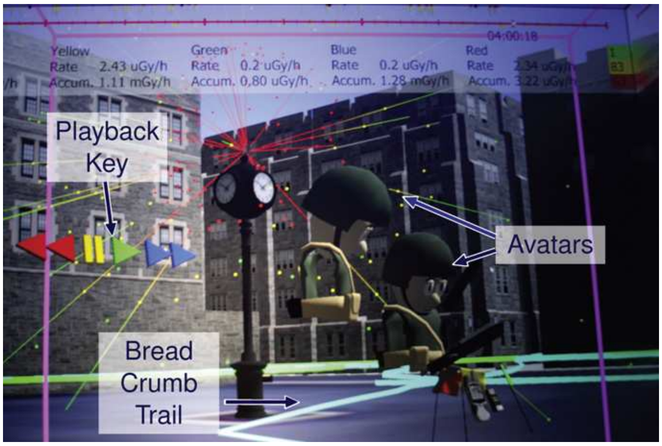

Fig. 9. Avatars in the AART indicate the position of each user's body and head, and the breadcrumb trail, seen here in cyan, indicates the path the team took during their survey. The HUD presents critical recording information, and the playback key provides a color coded reminder of wand functionality. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As the recording plays, objects, including measurement devices, move as they did in the recorded survey. In place of the glasses, users see avatars representing themselves. Because only the location and orientation of the head are known, and not the rest of the body, we represent only the user's head and torso. A point on the avatar's head where the tracker would be worn, roughly between the avatar's eyes, is snapped to the recorded location of the glasses. The location of the avatar's neck is then computed, and the torso is drawn vertically at this position, facing the direction the head is facing.A virtual representation of the wand moves as it did in the survey. The users also see a representation of the VR system, drawn as a wireframe cube representing the seams between the physical display walls. Fig. 9 shows an example of avatars replaying the users' movements.

To control the playback of the recording, the reviewer taps or holds buttons on the wand. To help the user easily use the controls, a color coded interface legend (key) appears to float at the wand, also shown in Fig. 9. The user can skip to the previous or next bookmark, pause playback, or resume playback. Holding the skip buttons controls the playback direction and speed, accelerating as the button continues to be depressed. The reviewer can also toggle a control that snaps them to, and moves them along, the path taken during the survey exercise. When this snapping is enabled, the reviewer can disregard traveling in the virtual world with the hat switch, and the display walls always align with the wireframe cube that represents them in the recording. If the snapping is disabled, the reviewer is free to fly anywhere in the virtual world without collisions.

The reviewer is also given an Identifinder, which initially is placed on his or her virtual belt. The Identifinder functions just as it does in the VST and allows the reviewer to show the trainees what readings they would have obtained if they had behaved differently. When the Identifinder is grabbed, the playback controls are disabled and the interface legend disappears. At this point, the wand buttons control the Identifinder. When the Identifinder is released, the key appears on the wand again.

The reviewer who used the system during an exercise noted that he would sometimes release the Identifinder but not place it on his belt, so it was floating in the virtual world. He would then skip to a bookmark, with the travel snapping enabled, and be moved to the team's location at that time in the survey. But because the Identifinder had not moved with him, he had to waste time skipping back in the timeline or trying to find it himself.

Another tool available to the reviewer is a *bread crumb trail*, shown in Fig. 9. This is a line drawn in the virtual world wherever the team traveled, and is calculated when the recording is loaded. It creates a new point on the line whenever the translation of the wireframe walls moves farther than five feet from the previous bread crumb point. Given that recordings can possibly reach lengths measured in several hours, this sparse point picking was chosen to try to reduce the cost of rendering each segment of this line. Because segments of the trail representing different times are all visible at once, the color of the line changes to indicate the time it represents.

The radiation visualizer discussed in Section 3.6 is used in the AART as well, displaying a particle system at each of the sources. This assists the trainees in understanding the effects of shielding and explaining the radiation readings they saw.

7. Evaluation

7.1. Exercise 1

The user study was conducted prior to some of the improvements to the system described here. Because the study made use of a 4-sided CAVE, users were not fully surrounded by displays and they used the 4-sided navigation techniques described in Section 3.3. Users could not place objects on their belts, but still had belts with flags and the Identifinder. Either wand could interact with either belt; however, each belt only became visible when the owner's wand was near. Collision detection was always based on the first user's head tracked position, regardless of which perspective method was used or which user was navigating.

We conducted a preliminary user study to evaluate the VST and improve the simulation. Additionally, we investigated several perspective and navigation methods specific to cooperative two-person teams in an IVE. The study was conducted over a period of two days with 8 participants from a CST, two of whom had tested our earlier prototypes and provided recommendations for improving the system. Although these two participants had experience using prior versions of the VST, it had substantially changed since they had last used it, and neither had experienced the specific scenarios used for the study nor the multi-perspective rendering technique. We wish to emphasize the importance of expert users in this study, as we were able to evaluate them using a real application comprising complex tasks with which the users were already familiar. Most of the users had no prior experience with VR but were familiar with training simulators or video games. Since the participants were members of the military who were under orders to use the VST for training, great care was taken to ensure that participation in the user study component was not coerced. Consent was obtained privately, and this information was not disclosed to the participant's commanding officers nor the other CST members. Next, the CAVE and equipment were demonstrated to all the participants as a group, and a brief training environment was loaded. After each two-person team was given several minutes to practice moving and using the virtual equipment, the participants left the facility so that the experiment could begin. During the experiment, participants wore their personal protective equipment and carried a two-way radio for communication with an off-site commander as if they were actually in the field. The teams took turns in the IVE for each stage in the experiment, with each team running isolated from the other participants, who waited in separate waiting areas. Thus, each team was given at least 2 h to rest between stages.

For Stage 1, each team participated in a perspectives experiment. This experiment was designed to compare four different perspectives for rendering the environment. In *first multi-perspective*, the environment was rendered from the first user's perspective and each user's instruments were rendered from their own perspective. In *first single perspective*, everything was rendered from the first user's perspective. In *second multi-perspective*, the environment was rendered from the second user's perspective and each user's instruments were rendered from their own perspective. In *second single perspective*, everything rendered from the second user's perspective.

During this experiment, hat switch navigation was disabled and each team was given a total of 16 flag-placing tasks to complete by walking around the CAVE. Each task required the participants to use their instruments and place either a yellow or red flag at a reading of 25 or 100 μGy/h, respectively.The tasks were evenly distributed among the four perspective types with respect to task type (red or yellow flags) and difficulty (involving shielding from the environment or not). The tasks were grouped according to perspective type and presented in random order within each group. The overall order of the perspective groups was counterbalanced using a Latin Square design. After each task, each participant was asked to rate how difficult it was to complete the task on a 5-point scale ranging from very easy to very difficult. Each was not aware of their partner's rating. After completing all the tasks, the participants completed a perspectives questionnaire which included both quantitative and qualitative responses relating to perspective.

For Stage 2, the participants first filled out the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) to obtain a baseline reading for simulator sickness [25]. The teams then completed the first of the four scenarios created by a CST science officer using the SDT. The first scenario had an outdoor explosion that scattered radioactive sources over an open area. The second scenario involved sources under vehicles, which provided shielding and demonstrated the need for surveyors to survey the areas above and below them. The third scenario had a strong source that was well shielded in most directions, requiring cautious surveying around corners. The fourth scenario involved several sources in a complex indoor environment. A narrative for these scenarios was developed by the science officer and presented to users as a series of escalating attacks.

During each scenario, the task completion time and the final radiation reading were recorded for future analysis. After completing the scenario, each participant filled out the SSQ post-test, the NASA Task Load Index (TLX) to assess workload [26], and the Slater-Usoh-Steed Presence questionnaire [27]. Stages 3 through 5 repeated this process for each of the remaining radiological scenarios. For Stage 2 and Stage 3, the first user controlled navigation using the wand. For Stage 4 and Stage 5, the wand navigation alternated between the first and second users between scenarios (the order of which was balanced across groups).We used a model of the United States Military Academy at West Point campus as an environment which was unfamiliar to most of the CST members in our study.

After completing all stages, each team was then interviewed privately by one of the experimenters. The interviews were semi-structured with questions relating to general feedback, training value, perspective types, navigation methods, manipulating objects, and possible future improvements to the system. The interviews were video recorded and later converted to text transcripts. The qualitative feedback gained from these interviews has been and will be used to improve the simulator in the future.

7.2. Exercise 2

The second exercise was similar to the first exercise, but we had improved the system since it was performed. The primary improvement to the system was the addition of the AART. Also, the system now ran in a six-sided CAVE-like display, so hat switch navigation behaved differently than it did in the previous exercise. This time, four CST members that had previous experience with the system trained for two days, using two new scenarios. The first involved several sources in a large outdoor urban environment, where several intentionally difficult shielding scenarios were incorporated. The second scenario was an indoor environment with complex shielding effects. Both scenarios contained clues as to the location of the sources, such as threatening notes in key locations.

These scenarios were designed to require more time than the scenarios of the previous exercise. Unlike the previous exercise, the scenarios were also persistent between pairs of CST surveyors. Once a team finished surveying, they would exit the IVE and discuss their findings with the commander and the next pair, who would then resume the survey where the previous pair left off. The surveyors could choose their equipment from a virtual table upon entry into the virtual world. This way, the team could distribute equipment however they liked, unlike the previous exercise where certain equipment was always bound to a particular wand. Over two additional days, this was repeated with four members of a different CST, who had not previously experienced the system. The study of multi-perspective rendering was not performed during this exercise, as conclusive results had already been obtained, but we did gather results in the interviews with regard to navigation preferences.

8. Results

8.1. Quantitative data

8.1.1. Perspectives exercise

For the perspectives experiment performed during the first exercise, the average difficulty ratings were computed for each perspective type: first multi-perspective ($M = 2.16$, $SD = 0.73$), first single perspective ($M = 3.09$, $SD = 1.38$), second multi-perspective ($M = 1.94$, $SD = 0.83$), and second single perspective ($M = 2.78$, $SD = 1.31$). A 2×2 repeated-measures analysis of variance (ANOVA) was performed with a significance level of $\alpha = 0.05$, testing the within-subjects effects of instrument perspective (multiple or single) and user perspective (first or second). The analysis revealed a significant main effect for instrument perspective, $F(1,7) = 14.59$, $p = 0.01$, $partial\ \eta^2 = 0.68$. The main effect for user perspective was not significant, $p = 0.51$, nor was the interaction effect, $p = 0.93$.

These results show that multi-perspective rendering of instruments reduces task difficulty over single perspective rendering. This is an intuitive result, since geometric distortions in closely located objects would be more noticeable than distant objects in the environment, which can negatively influence the readability of the numerical displays on personal instruments. Though ratings for the first user perspective conditions were slightly easier on average, the differences were not strong enough to be significant. We had expected that the first participant should be given the correct perspective over the second user, so this is an interesting result. Overall, the instrument perspective method seems to be a more important factor than which user receives the correct environment perspective.

8.1.2. First exercise scenarios

The number of participants was too few for statistical analyses to yield any meaningful results for the data collected during the radiological exercises. However, useful information can still be obtained from examining this data. Table 1 shows the mean results for each of the four radiological scenarios. Scores on the presence questionnaire were high, with 30% of ratings receiving a 6 or higher on a 7-point Likert scale. On average, ratings were slightly lower in the first scenario, but increased for the later scenarios. It is likely that participants became more immersed as their familiarity with the equipment increased and as they became engrossed in the narrative storyline that extended across the scenarios. NASA TLX workload scores indicated that the task imposed a workload which was not excessively taxing. As expected, the workload was higher for the final scenario, which was intended to be the most difficult.

Table 1
Mean user study results for each of the four radiological scenarios.

Measure		*Ex. 1*	*Ex. 2*	*Ex. 3*	*Ex. 4*
Presence	*M*	4.12	4.56	4.44	5.08
(1-7)	*SD*	1.03	1.11	1.62	0.81
Workload	*M*	30.70	25.79	28.92	37.83
(0-100)	*SD*	22.54	29.84	28.47	30.50
SSQ Increase	*M*	2.67	2.67	4.81	3.74
(0-235)	*SD*	2.83	5.60	4.69	5.29
Completion Time	*M*	39.50	26.50	18.75	31.00
(minutes)	*SD*	10.30	3.59	3.06	3.78
Radiation Exposure	*M*	75.15	32.79	43.30	575.75
(μGy)	*SD*	93.13	43.48	22.96	416.95

Completing the survey quickly is important for limiting radiation exposure. The first three scenarios were designed to take approximately a half-hour each to complete, and the final scenario was designed to last 1 h. Mean completion time for the first scenario was longer than expected, which was likely due to unfamiliarity with the simulator. Completion times dropped considerably over the next two scenarios. The standard deviation for the first scenario was about three times higher than the other scenarios, which indicates that as participants became more familiar with the simulator, the time taken to complete the task became more consistent across groups.

Retrospectively observing the overall simulated radiation exposure is a unique training benefit of this system. Exposures for the first three scenarios were well within safe limits. The exposure for the last scenario was much higher, but this was expected since this scenario was designed to be more difficult. The highest recorded dose was 1173 μGy, which is 2.3% of the yearly federal limit for radiation workers in the United States.

One participant did report high levels of simulator sickness with an SSQ score of 164.56 for one of the scenarios. This participant noticed the onset of simulator sickness and continued without reporting it until the scenario was complete and symptoms were severe. This experience highlights the importance for users, especially military users, not to try to work through simulator sickness. In order to avoid skewing the data, we eliminated this outlier from mean calculation. Despite the fact that participants were immersed frequently over the course of two days for a long amount of time, the simulator sickness scores for the remaining seven participants were very low. This result is promising for future training which requires long periods of immersion to be effective, though simulator sickness remains a concern for those prone to experiencing these symptoms.

8.1.3. Second exercise scenarios

Like the first exercise, the number of participants in the second exercise was too few for meaningful results to be obtained from the statistical analysis. Again, we can still gather useful information from the data. Scores on the presence questionnaire were higher than those from the first exercise, with 37% of ratings receiving a 6 or higher on a 7-point Likert scale. On average, ratings were slightly lower for the second scenario. We suspect that this may be attributed to errors in our collision detection, which are more prevalent in the second scenario's indoor environment where collisions are more likely. Unfortunately, the NASA TLX was incorrectly administered.

The scenarios in the second exercise were designed so that the teams alternated while the scenario persisted. During this process, the off-site commander would determine when the teams would alternate based on their performance. Although both CST groups completed the same scenarios, no consistent condition was in place for alternating teams. Therefore, the objectives for each team's entry were not consistent. Thus, no meaningful analysis of each team's completion times can be performed.

Like the first exercise, accumulated exposures for each CST member was well within safe limits. Exposures for the second scenario were generally about twice those from the first scenario. This was unsurprising due to the complex nature of the second scenario's indoor environment. The highest recorded dose during the study was 41 μGy, which is only 0.08% of the yearly federal limit for radiation workers in the United States.

Young et al. concluded that when using a self-reported questionnaire, like the SSQ, reports of simulator sickness were much greater when both a pre and post test were given than when only a post test was given [28]. Therefore, we did not administer the SSQ pre-test. The highest reported SSQ post-test score was 104.72, though without the pre-test, we are unable to know how this participant was feeling before entering the simulator. However, the scores of the other participants were low.

8.2. Qualitative data

8.2.1. First exercise

The perspectives questionnaire yielded a number of interesting qualitative comments from participants. While multi-perspective rendering was generally favored, one participant noted an important tradeoff introduced by rendering instrumentation from multiple perspective simultaneously: "The user's instrumentation and partner's instrumentation are frequently obscuring each other's view of their own instrumentation and the virtual environment in which they are operating". Some participants figured out how to work around this difficulty by communicating to guide their partner's head orientation so that the controls would be readable. We also observed that for some teams, one member would move his body or his virtual equipment out of the way so that the other member could perform his task. Another team physically oriented themselves so that each user could see his equipment and rely only on the hat switch for movement. Additionally, participants also commented positively on the simulator's realism, which supports the increase in presence scores over the course of the study: "The longer I spent in the VR world, the more I felt I was actually there".

In interviewing the participants after the exercise, we gained additional qualitative data. Although the ratings of the different perspective modes did not indicate a strong preference for giving a particular user the world perspective, the participants did vocalize a distinct preference for giving the world perspective to the user that is navigating. Additionally, most participants felt that the first user should be in charge of navigation. One team found that because the multi-perspective rendering technique allowed one user to potentially see the other user's equipment, the training value was reduced since a user could read the equipment himself without communicating with his partner.

Although the collision detection was always bound to the first user, this was never cited by CST members as a reason for feeling that the first user should navigate. The user that was navigating should have experienced correct collision detection; we overlooked this step when implementing the system that allowed us to switch between perspective and navigation modes.

Overall, most users felt that our system provided useful training. Particularly, they noted that the system enabled them to experience realistic equipment readings and gain a better understanding of the amount of exposure they would encounter in a real survey. They said that the shielding model behaved accurately, giving them a more realistic experience than alternative training methods. Several users felt that the scenarios were realistic and closely resembled real world missions. Several users also noted that the system provided a safe environment in which mistakes had no physical consequences and remarked that this training was an improvement over other training methods they had experienced. Some users gave strong positive feedback about the system's training value, like saying the system is second only to real world training with live radiological sources and that it was realistic and very user friendly. Many subjects saw potential for RIST to be extended into other training areas. In addition to training for other CST responses, such as biological and chemical threats, some also saw potential for law enforcement and military combat training.

8.2.2. Second exercise

The second exercise gave us an opportunity to get more feedback on the training value of the system, which had been improved. Many of the previously discussed results were confirmed in this exercise. Either user could now navigate with the wand, so the choice of who would navigate was purely up to the team. Again, the consensus among both groups was that the first user should be responsible for navigation. Comments from the team whose members were inexperienced with our system were quite similar to comments we received from the experienced team during the previous exercise. In particular, they noted how the multi-perspective rendering sometimes caused one user's equipment to occlude the other user's view. Some of the participants from the inexperienced team found the same solution to this problem as the experienced team had previously found. They found positions that did not interfere with each other's views and did not move from them.

It was interesting to observe the alternating teams share information about the scenario. They seemed to speak about the virtual world as if it was a real place where they had actually been. This could have even helped the sense of presence of the surveyors that then entered the virtual world.

Because we designed the system based on information given to us by members of the experienced CST, we were surprised when the inexperienced team noted that the VR system imposed an inherent limitation on some of the strategies they use when surveying. A common practice in their group is for the surveyors to separate, and one person surveys while the other performs separate tasks. Because it is not possible for the users of RIST to separate further than the VR display screens allow, this was different than the way they were used to performing surveys.

The CST science officer that performed the after action reviews during the second exercise had many positive things to say about the After Action Review Tool. "The AART is probably one of the best parts of virtual training. Being able to learn what we do well or not so well is where the real training value is realized. The AART is a very concise way of visualizing the conduct of a mission. It is especially useful when multiple teams conduct sequential entries as it allows all teams to see the whole mission, not just the part they were involved in" [29].

All the comments from the participants about the AART were also quite positive. In general, they found it very useful to see a visualization of how the radiation from a source was shielded by the environment. One participant noted that an important part of the AART was the presence of the science officer, because he was able to explain the shielding effects that were being visualized by the tool and provide suggestions for how they could have improved their performance.

A consistent comment we noted was each participant's impression of the program's lack of visual quality. This is unsurprising, as we have focused our efforts on developing the interaction techniques and tools necessary to perform a virtual survey, instead of improving the graphics of the program.

9. Conclusions and future work

We have presented an immersive radiological training system that simulates the environment and required equipment for Army National Guard Civil Support Teams. The overall system also includes a scenario design tool and an after action review application. We also developed a novel perspective rendering technique for multiple users to train simultaneously in a typically single-user VR system. To evaluate the effects of this technique, as well as the effects of which user navigates, we conducted a user study using CST members. While the multi-perspective method does have some occlusion problems, we found that it was easier for the CST members to accomplish tasks using our technique. We also found that CST members preferred that navigation should be the front user's responsibility. We used this system to train members of the CST, who in general gave positive feedback regarding its training value. The training exercises also gave us valuable feedback about the system and how it can be improved.

We plan to make many improvements to RIST. Simulation of more types of radiation, including alpha and beta radiation, will make it possible to simulate different complex scenarios. We would also like to add more virtual locations in which to create scenarios. We intend to improve the collision detection as well. Letting users control the GPS device with the wand buttons will make it more useful. We intend to improve the graphical quality of RIST. We also intend to improve the Identifinder controls in the AART, to prevent the reviewer from losing the device. Eliminating the abrupt movement of grabbed objects should also help make the grabbing system more intuitive.

During the second training exercise, the science officer working with us on this project was inside the VR system with the team while they surveyed. This was so that he could observe them and create bookmarks at important times. An alternative to this that may increase the realism the users experience is to allow this observer to use a computer outside the immersive display, and view the team's actions as represented by avatars.

We intend to network multiple VR systems and compare the effectiveness of using such a configuration to having multiple users working within the same physical space. This would also allow members to separate by distances larger than those possible in a single system. Full body tracking in the VST and AART would allow for exposure measurements for each part of the user's body, shielding of radiation by each user's body, accurate avatar posing in the AART, and the ability for users to lean over objects, since we would no longer assume their head to be over their feet. To allow the SDT user to customize the world and create unique scenarios, we would like to allow the user to modify the material properties of the scene's geometry.

Both teams had many good suggestions for other ways to improve the system. Adding a back light to the virtual device displays is a feature we plan to implement. Physical mock-ups of their real devices was an idea that came up during both exercises. Several participants made note of the absence of any sounds in our system. Not only would adding sound allow for useful features like an audible alarm on the AN/UDR-13, but it would also enable realistic ambient noise, like wind.

Some users found that matching readings in the AART HUD to the corresponding device was difficult. We may draw the readings in the virtual world next to each device, or color code the readings and devices. Rather than snapping the travel to match the recorded travel exactly, one user felt it would be beneficial to offset the travel away from the recorded travel, while still following it. Hopefully, moving the avatars slightly away from the users while still following them would be easier to view without the tracked glasses.

This system could easily be expanded to provide training for other types of scenarios. Different virtual tools can be added, allowing for training of other tasks that deal with radiation exposure, as well as simulations of chemical or biological threats that CSTs survey.

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