Virtual Environments for Shipboard Firefighting Training

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Abstract

A virtual environment (VE) of portions of the ex-USS Shadwell, *the Navy's full-scale fire research and test ship, has been developed to study the feasibility of using immersive VE as a tool for shipboard firefighting training and mission rehearsal. The VE system uses a head-mounted display and 3D joystick to allow users to navigate through and interact with the environment. Fire and smoke effects are added to simulate actual firefighting conditions. This paper describes the feasibility tests that were performed aboard the* Shadwell *and presents promising results of the benefits of VE training over conventional training methods.*

Background

Shipboard fires are a very serious problem for the Navy, and the Naval Research Laboratory is investigating ways of using virtual environments to improve shipboard firefighting performance. VE is seen as an area with great potential for firefighter mission preparation, rehearsal, and training. VE provides a flexible synthetic environment where firefighters can familiarize themselves with an unfamiliar part of the ship, practice firefighting procedures by interacting with simulated fire and smoke, and test firefighting tactics and strategies without risking lives or property. The Navy has recognized the need to develop ways of using VE for training through the establishment of the Virtual Environment Training Technology (VETT) program [1] with emphasis placed on specific Navy application areas [2]. Shipboard firefighting is an area of special interest to the Navy, with applicability to the commercial sector.

Many VE prototype demonstration systems show great potential for training purposes, but to be used as an effective training tool, validations are necessary. Validated VE training task areas include astronaut training for the Hubble Space Telescope repair mission [3] and the training of Naval submarine officers in harbor navigation [2]. We do not attempt to use VE for training firefighting tasks (since our subjects are trained firefighters), but to use it as an aid to mission preparation.

An additional factor in shipboard firefighting is stress. VE technology has been shown to produce successful results in overcoming stressful situations such as fear of heights [4] or fear of flying [5]. For shipboard firefighting, our intent is not to overcome fear, but to acclimate the user to the expected stressful situation. The work reported here examines and validates the effectiveness of VE for mission preparation in a stressful environment.

The Navy uses the ex-USS *Shadwell* [6], a decommissioned ship maintained by NRL in Mobile, Alabama, as its full-scale fire and damage control research, development, test and evaluation platform. Experimental results of previous tests performed on the *Shadwell* have shown that two factors that significantly affect a firefighter's ability to fight a fire are visibility and familiarization with the compartments near the fire [7]. Reduced visibility due to smoke can be accurately simulated in VE, and familiarity with a physical space can be gained by navigating through its model in VE [8]. A VE test system was developed and feasibility tests were conducted on Sept. 18-22, 1995 aboard the *Shadwell* to determine if VE can be used to reduce the effects of these two factors, and to evaluate the feasibility of using immersive VE as a mission preparation tool for firefighters. The tests were performed under realistic

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14. ABSTRACT
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conditions with real shipboard fires, using Navy firefighting teams.

Objective

The objective of our study was to determine the effectiveness of training and mission rehearsal in VE on the navigation and firefighting performance of trained firefighters under realistic conditions in unfamiliar ship's spaces.

The *Shadwell* Environment

A full scale virtual model of the *Shadwell* was developed for areas of the ship that were to be used for the feasibility tests. The model comprises portions of the superstructure deck, the main deck, and the second deck. Texture maps for bulkheads and decks were created from photographs taken aboard the *Shadwell*. A common bulkhead texture map was used for most bulkheads, except in special cases where the appearance of specific, noticeable details might serve as landmarks in the navigation process. In those cases, photographs of the significant landmarks were used for the texture maps.

All of the compartments, passageways, stairs, doors, and hatches in the test area were accurately modeled. Obstructions such as tables, lockers, and safety chains were included in the model to correctly characterize the navigable areas of the ship. Terrain following and collision detection were used to realistically simulate the paths users would use on the ship. Thus users "walked" down stairs and along passageways and "collided" with obstructions in the virtual environment. Figure 1 is a view of a portion of the test area.

Fig. 1 - A view of the *Shadwell* test area.

Users navigated with a custom-made 3D joystick using a "fly where you point" metaphor. A glove avatar which followed the position of the 3D joystick provided visual feedback to allow the user to readily see the direction of motion. The "fly where you point" metaphor allowed the user to proceed in the direction he or she was pointing, while actively looking around in the environment. This method is an alternative to the more common "fly where you look" metaphor, which does not let the user move in one direction while looking in another.

The glove avatar was also used for interaction with doors. The doors were "opened" and "closed" by pointing the avatar directly at the door and pressing the appropriate button on the joystick. The door motion continued only as long as the button was pressed, so small changes in the position of the doors were possible. Figure 2 shows the view along a passageway with the glove avatar in the process of opening the door on the right.

Fig. 2 - View of a *Shadwell* passage-way with glove avatar opening door.

Where possible, accurate 3D models of shipboard items were used, but items that did not require any interaction, such as fire hoses and oxygen breathing apparatus (OBA) racks, were sometimes modeled as simple polygons with texture maps in order to reduce the graphics rendering load. The user interaction extends methods used at the Navy Postgraduate School [9], with modifications and additions to support the 3D joystick interface, the "fly where you point" metaphor, and improved fire and smoke simulation.

In addition to the *Shadwell* model used for the actual testing, a practice model was built to allow the users to familiarize themselves with the interface to the virtual environment. The practice model included all the components of the *Shadwell* model, but it did not represent any portion of the real ship. Participants used the practice model until they felt comfortable with the VE controls and display thus preventing unfamiliarity with the interface from interfering with the test results.

Visual simulation of fire and smoke effects was included in the VE. Dynamic growth of a texture-based fire simulation was used to provide realistic behavior to the fire. The smoke model was coupled to the fire growth to produce an effective combination of fire and smoke. Both an ambient smoke model and a texture-based smoke turbulence model were included to produce distant and nearby smoke effects. Figure 3 shows the fire and smoke simulation along with several of the obstructions in the test area.

Fig. 3 - View of simulated fire, smoke, and obstructions.

A Virtual Research VR4 head-mounted display (HMD) was used for viewing the environment. Two channels of a Polhemus Fastrak electromagnetic tracking device tracked the user's viewpoint and the position and orientation of the 3D joystick. The joystick used a dual position rocker switch for controlling the forward/backward movement, and separate open and close buttons for operating the doors. The simulation ran on a Silicon Graphics dual-R4400 200 MHz Onyx with Reality Engine II (RE2) Graphics and two Raster Managers using software based on the Iris Performer libraries.

Technical Approach

The feasibility test was divided into two phases. The first phase was a navigation task that did not involve fighting a fire. This phase was designed to eliminate any stress, anxiety, or safety issues that might arise in a firefighting scenario. The firefighters wore an OBA, which is part of their normal firefighting ensemble, with a special LCD faceplate installed to simulate a smoke-filled environment. The participant's task was to traverse a specified path through the *Shadwell* in a simulated smoke-filled environment. This test was designed to evaluate the effectiveness of VE for training shipboard familiarization under reduced visibility. No firefighting skills were involved in this phase, so variability between test participants in firefighter training and experience was not a factor. Data collected for Phase 1 included the time taken to accomplish the task and the number of wrong turns taken during the test.

Phase 2 was an actual firefighting task requiring the participant to locate and retrieve specific firefighting equipment, perform standard firefighting preparatory procedures, and lead the firefighting team to extinguish a real shipboard fire. This phase was designed to evaluate whether or not VE helps firefighters actually extinguish a fire faster than firefighters without VE training. During this test, the participants functioned as the fire party Team Leader, and members of the *Shadwell* safety team and the Afloat Training Group served as the fire party teams.

The two areas of the *Shadwell* used for Phase 1 and Phase 2 did not overlap, thus any familiarization gained in the Phase 1 test run could not be transferred to the Phase 2 run.

Test Participants

An important consideration in selecting participants for this test was to use only trained Navy firefighters. The Navy has unique requirements, tactics, and training for firefighters, and since Navy personnel are the intended users of this type of VE training, it was important to have potential users as test participants. Twelve enlisted personnel participated, eight men from the USS *Inchon* (MCS-12) and four women from the USS *Puget Sound* (AD-38). The participants were all qualified in shipboard firefighting. None of the participants were familiar with the *Shadwell*. The test participants were divided into a Traditional Training group and a VE Training group. To prevent any gender bias in the test results, the males and females were divided equally between the two groups.

Test Procedure: Phase 1 - Navigation

The test procedure for Phase 1 is listed in Table 1. Phase 1 began with a Mission Review presentation by the Test Director who defined the task and used ship's diagrams to show the route to be followed. The Mission Review for this phase was presented to all participants as a group, but they completed the navigation test individually. Participants were instructed to maintain existing door closures (which is standard procedure under certain conditions on ships), but that they would be given assistance opening and closing doors if needed. They were told if they turned the wrong way, the only correction they would receive was being told “Wrong way”. Detailed instructions were provided both orally with diagrams and with a written Mission Statement which described the path to be traversed during the test and the intended goal. Participants were told they would be timed from when they opened the first door until they reached the goal. They were instructed to move through the course as quickly as possible, making as few mistakes as possible. Specific details of the path are available in [10] and [11]. Phase 1 required the traversal of 3 decks, 4 doors, 3 passageways, 2 inclined ladders, and 1 compartment, with 8 possible wrong turns, to achieve a single goal (touch a porthole), covering an approximate distance of 80 feet.

Table 1 - Phase 1 Test Procedure

1. Mission Review - Test Director defines task and route.
2. Mission Rehearsal - participants study DC Plates and Mission Statement.
3. VE Rehearsal (VE group only) - participants practice their mission in VE.
4. Shipboard Navigation Test - participants perform task aboard *Shadwell* and performance measurements are recorded.

Just prior to an individual’s turn to take the test, they were given five minutes for Mission Rehearsal where they could study the DC plates and the written Mission Statement. DC Plates are a collection of isometric views of a ship which, taken together, detail the ship’s systems. The plates are commonly used aboard ships, and all participants were familiar with them. The DC plates used for this test show only the structural layout of the ship since no other details were necessary for the test. Portions of the DC plates that show the test area can be found in [10] and [11]. Figure 4 shows the Mission Statement used for the Phase 1 tests.

After completing their Mission Rehearsal, the Traditional Training group proceeded to take the Phase 1 test. The VE Training group proceeded to the VE Rehearsal prior to taking the test.

For the VE Rehearsal, participants practiced their mission immersed in an accurate model of the test space. The VE Rehearsal was performed in three steps. Step 1 was the “magic carpet ride” where the motion through the space was controlled by the computer, and the participant was instructed to look around and familiarize themselves with the spaces. This step was narrated to point out various notable features in the model. During Step 2, the participant navigated through the space by operating the motion and interaction controls described earlier. For Step 3, the participant again controlled the motion and interaction, but simulated smoke which limited visibility to about three feet was added to the environment. Timing measurements were collected during the VE Rehearsal, both the time it took for each participant to walk through in clear visibility and in reduced visibility. The VE Rehearsal was also recorded on video. A one minute rest period was taken between each of the VE Rehearsal steps. During this period, the HMD was removed and the participant was checked for simulator sickness before beginning the next step.

NAVIGATION TEST (PHASE I)
MISSION STATEMENT

GOAL: To navigate through the forward section of the ex-*Shadwell* under *reduced visibility conditions* and locate a hole on the starboard side of the ship.

NAVIGATION MISSION: The navigation mission will be initiated on the superstructure deck at WTD 01-29-1 which is located forward of the mess deck. You will proceed to the starboard side and traverse down an inclined ladder to the main deck. You will then locate and traverse down a second inclined ladder to the second deck and proceed forward to compartment 2-22-3-L (ARMY OFFR'S & NON COMM WR / WC) and note the hole in the side of the ship.

TEST PROTOCOL: The following general guidelines will be applicable to all test participants during the Phase I testing:

(1) Each test participant will traverse through the test area individually.

(2) Each participant will don and activate an OBA prior to initiating the navigation mission. (NOTE: A smoke simulator will be fitted to the face piece).

(3) Each participant should strive to transit the test area in an expeditious manner.

(4) Misdirections will be verbally corrected, "WRONG WAY".

(5) Test participants will be required to maintain *existing* door closures.

(6) The mission will be complete when the test participant touches the hole in the side of the ship.

Fig. 4 – Mission statement for Phase 1.

Before beginning the Phase 1 test run, the participants donned an OBA with a special smoke simulator faceplate. The device was adjusted so that visibility was reduced to approximately three feet. A *Shadwell* safety team member accompanied the participant throughout the test and collected data on the elapsed time, the number of wrong turns taken, and the number of times assistance was provided with doors.

Test Procedure: Phase 2 - Firefighting

The test procedure for Phase 2 is listed in Table 2. Because Phase 2 involved actual firefighting, the participants were first given a Team Leader Review that went over safety issues, firefighting tactics and strategies, and the duties they would perform as Team Leader. During the Mission Review, the locations of the necessary equipment and the location of the fire were shown on the diagrams. The functions to be performed in this test were to locate and don the OBA, assemble and direct the firefighting Attack Team, find and prepare the designated fire hose, and locate and extinguish the fire. Participants were responsible for making sure their team members were properly outfitted (including operational OBAs), locating and preparing the firefighting equipment, locating the fire compartment, positioning their team for proper door entry, assessing the fire, and directing the fire attack. Phase 2 required traversal of 2 decks, 2 passageways, 1 inclined ladder, 3 compartments, 4 doors, with 9 possible wrong turns, to achieve 3 goals (locate equipment, prepare team, and extinguish fire), for an approximate distance of 70 feet (see [10] and [11] for details). The Mission Review was performed in the same manner as in Phase 1, except that this time it was performed on a individual basis. After the Mission Review, participants were given 10 minutes for Mission Rehearsal with the DC plates and the Mission Statement shown in Fig. 5.

After Mission Rehearsal, the VE Training group proceeded to VE Rehearsal. The Phase 2 VE Rehearsal used the same three step process as was used in Phase 1. This time the goals of getting the OBA, joining the team, retrieving the fire hose, and attacking the fire were all included. Step 1 was the “magic carpet ride” where the participant was instructed to look around to become familiar with the space, and the narration pointed out various obstacles and hazards along the path. For Step 2, the participant was required to navigate the space, to find the OBA, the team staging area, and the fire hose locations, and to arrive at the fire location. For Step 3, the same functions were performed as in Step 2, but simulated fire and smoke were added at the location of the shipboard fire. One minute rest periods were again provided between steps to eliminate possible simulator sickness. The model of the fire space was an accurate replication of the fire compartment, including a trip hazard along the path and three lockers blocking immediate access to the fire.

Table 2 - Phase 2 Test Procedure

1. Team Leader Review - Test Director reviews safety procedures, firefighting tactics, and Team Leader duties.
2. Mission Review - Test Director defines task, shows locations of equipment, team staging area, and fire.
3. Mission Rehearsal - participants study DC Plates and Mission Statement.
4. VE Rehearsal (VE group only) - participants practice their mission in VE.
5. Exercise Brief - participants discuss mission plans with Attack Team.
6. Shipboard Firefighting Test - participants perform task aboard *Shadwell* and performance measurements are recorded.
5. Debrief - Test Director and Attack Team evaluate participant’s performance.

After the Traditional Training group completed their Mission Rehearsal, the participants proceeded to an Exercise Brief with the Attack Team in which they reviewed the mission and instructed the team on nozzle settings and hand signals. The VE Training group began their Exercise Brief after the VE Rehearsal. They then went to the staging area to dress in protective clothing and prepare for the firefighting test run.

Shipboard Fire Characteristics

The fire for the Phase 2 test was a steady state Class A fire. A wood crib was made from red oak cut to 2 by 2 by 48 inches with 10 rows of 10 boards that were 2 inches apart. The crib was assembled on a metal stand 23 inches high and ignited with 5 gallons of heptane in a 36 inch square pan below the wood crib stand. The fire was allowed to burn for approximately 7 minutes to produce a sizable fire, and to allow the heptane used for ignition to be completely burned away. Research into the physical characteristics of fires conducted aboard the *Shadwell* has given the test personnel the ability to reproduce many types of fires within close tolerance. The fire test spaces are well instrumented and various combustion parameters are closely monitored in the *Shadwell*'s Control Room.

The Attack Team members serving as nozzlemen and hosemen were senior firefighters from the Afloat Training Group Middle Pacific, or from the *Shadwell* safety teams. Safety team members from the *Shadwell* also acted as plugmen and door entrymen. Participants were instructed that they were in charge except that any call by a safety team member must be followed without explanation. No safety calls were needed during the tests.

**FIREFIGHTING TEST (PHASE II)
MISSION STATEMENT**

GOAL: To navigate through the forward section of the ex-*Shadwell* under realistic shipboard fire conditions and extinguish a Class A compartment fire.

FIRE MISSION: The fire mission will be initiated on the forecastle (main deck) at WTD 1-13-1. You will proceed down an inclined ladder to the second deck into the Repair Two area. Once in the Repair Two area, you will locate compartment 2-11-2-Q (BATTLE DRESSING STATION) and retrieve and don your OBA. You will then lead the assembled attack team down the starboard passageway, locate the FPL 2-19-3 fire station, and initiate a direct attack on the Class A fire in compartment 2-15-2-A (STOREROOM).

TEST PROTOCOL: The following general guidelines will be applicable to all test participants during the Phase II testing:

(1) All test participants will function as the Attack Team Leader.

(2) Each participant will don a complete firefighting ensemble (except OBA) prior to commencing the fire mission.

(3) Each test participant will be responsible for leading the fire attack and strive to maintain a rapid, continuous, and aggressive response to the firefighting actions.

(4) Misdirections will be verbally corrected, "WRONG WAY".

(5) Maintaining existing door closures *will not* be required during Phase II testing.

(6) The mission will be complete when the fire is reported out or when terminated by a safety team member.

Fig. 5 – Mission statement for Phase 2.

After the Phase 2 fire, participants attended a Debrief Session where they discussed their performance with the Test Director and Attack Team. They also provided comments about whether VE Training was helpful to them.

Findings

Our results show that there was a measurable improvement in the performance of firefighters that used VE for mission rehearsal over firefighters without VE in both phases of the test. In the Phase 1 (navigation) test, the VE Training group was an average of 30 seconds faster over a two minute run (see Table 3). The VE Group averaged 1:54 (σ = 1:03) while the Traditional Training group averaged 2:38 (σ = 0:59). These results give an indication of benefits of VE training, although further studies with a larger group size are warranted before statistical significance is evident. In addition, all of the Traditional Training group members made at least one wrong turn, while only one VE Training group member made any wrong turns. In time-critical applications such as shipboard firefighting, both traversal time and wrong turns can contribute significantly to the outcome of the firefighting evolution. These results indicate that VE training shows promise in producing a performance improvement in shipboard familiarization and navigation.

Table 3 - Phase 1 Test Results

Subj.	VE/Trad.	Wrong way	Time
1.	V	0	1:13
2.	V	0	1:14
3.	V	N.A.	N.A.
4.	V	0	1:35
5.	V	0	1:45
6.	V	3	3:43
7.	T	1	1:18
8.	T	1	1:49
9.	T	1	2:43
10.	T	2	2:50
11.	T	3	3:01
12.	T	2	4:07
VE average		0.6 (σ=1.3)	1:54(σ=1:03)
Trad. average		1.6 (σ=0.8)	2:38(σ=0:59)

*N.A. - not available due to invalid test run (restarted)

As an indicator of how fast the Phase 1 test could be traversed under ideal training conditions, five experienced firefighters from the Afloat Training Group completed the Phase 1 navigation run after rehearsing in the actual shipboard test space. They studied DC Plates for 10 minutes and were given three practice runs in the actual test space, similar to the way the VE Training group rehearsed their runs in VE. First they were guided through the route, then they walked the route under clear visibility, and third, they walked the route wearing reduced visibility goggles set to approximately three feet like the smoke simulator faceplate. After training, they ran the route wearing an OBA with a smoke simulator faceplate. From only two usable runs, the average time was 1:11. This suggests that VE training is not as good as training in the actual space, which is what should be expected.

In Phase 2 (the firefighting test), the VE Training group again showed better elapsed times for arriving at the fire scene and putting the fire out (see Table 4). For the arrival time at the fire scene, the VE Group averaged 6:55 (σ=0:42) while the Traditional Training group averaged 8:39 (σ=2:14). For the total time to extinguish the fire, the VE Group averaged 9:26 (σ=0:42) while the Traditional Training group averaged 11:43 (σ=2:29). All but one of the participants in the Traditional Training group made wrong turns in Phase 2, but no one in the VE Training group did. This supports the results from Phase 1 for this metric, and statistical significance is suggested, although larger test groups need to be studied to reinforce this evidence. These results suggest that VE training can contribute to improved firefighter performance by reducing the time to extinguish fires.

In addition to the quantifiable results obtained during the tests, anecdotal evidence provided by the test participants reinforces the effectiveness of VE for mission rehearsal. Participants expressed their increased confidence in performing their firefighting tasks because of the familiarization with the spaces and situational awareness that they received through VE. They were able to concentrate on their firefighting skills (the most important part of their task) rather than the problem of navigating through unfamiliar spaces. Most members of the VE Training group used VE to actively investigate the fire scene to locate notable landmarks and obstructions, possible ingress and egress routes, and to plan their firefighting strategies, enabling them to use their firefighting skills more effectively.

After testing, comments from one of the participants indicated that VE “helped me big time” and that he “went exactly there” [to the fire scene]. Another subject said that “VE really helped me” and that “the fire looked just like it did in VE”. One of the Traditional Training group members was allowed to use VE after his testing was finished, and indicated that VE would have helped him because without it he felt like he “went in there cold”.

Conclusions and Recommendations

The results suggest that virtual environments can be effectively used for training and mission rehearsal for shipboard firefighting. VE provides a flexible environment where a firefighter can not only learn an unfamiliar part of the ship, but also practice tactics and procedures for fighting a fire by interacting with simulated smoke and fire without risking lives or property.

These tests have proven to be a successful first step in the development of a new training technology for shipboard firefighting based on immersive virtual environments. The tests have also provided some insight toward potential areas of improvement that require additional research. User interaction techniques for manipulating objects in VE need further study, accompanied by usability studies to determine the

Table 4 - Phase 2 Test Results

Subj.	VE/Trad.	Wrong way	At Scene	Fire Out
5.	V	0	5:50	8:48
3.	V	0	6:56	8:52
4.	V	0	7:15	9:52
2.	V	0	6:21	10:11
6.	V	0	7:38	N.A.
1.	V	0	7:30	N.A.
11.	T	1	8:40	N.A.
7.	T	1	7:00	9:14
10.	T	1	6:20	9:35
9.	T	1	9:25	11:55
8.	T	1	7:53	12:28
12.	T	2	12:36	15:23
Trad. average		1.17 (σ=0.41)	8:39 (σ=2:14)	11:43 (σ=2:29)
VE average		0.00 (σ=0.00)	6:55 (σ=0:42)	9:26 (σ=0:42)

*N.A. - not available due to incomplete test data effectiveness or utility of those techniques. More natural and intuitive input/output devices such as 3D sound, speech and natural language input, integrated multimedia and hypermedia instruction, and multiuser interaction are all areas that could be used to provide an enhanced VE training system.

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