Human Factors Assessment in VR-based Firefighting Training in Maritime: A Pilot Study

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***Abstract*—Virtual Reality (VR) has been used for training aircraft pilots, maritime seafarers, operators, etc as it provides an immersive environment with realistic lifelike quality. We developed and implemented a VR-based Liquefied Natural Gas (LNG) firefighting simulation system with head-mounted displays (HMD) and novel human factors evaluation that could train and assess both technical and non-technical skills in the firefighting scenarios. The proposed human factors evaluation is based on a competence model and the non-technical skills such as situation awareness, vigilance, and decision making of seafarers could be assessed. An experiment was carried out with 6 trainees and 2 trainers using the implemented LNG firefighting simulation system. The results show that that the maritime trainees felt the VR scene was realistic to them, evoked similar emotions (such as fear, stress) during the demanding events as in the real world and made them attentive during the experience.**

Keywords- Virtual Reality, competence model, human factors, non-technical skills, maritime

I. INTRODUCTION

Due to its immersive nature, Virtual Reality (VR) has contributed to training pilots [1, 2], seafarers [3, 4], and surgeons [5] in aeronautical, marine and medical areas respectively. It has been proved that with the help of VR, the training efficiency has been significantly improved [1-5].

The VR head-mounted displays (HMD) have been consumer-ready since 2016, which boost various applications in different fields. In the maritime area, one of the training tasks is to prepare the cadets to observe the situation and make decisions in the case of unexpected leakage of fuel, such as Liquefied Natural Gas (LNG) which may result in fire. This firefighting task requires the cadets to meticulously follow all steps of a standard procedure to guarantee safety for everyone involved. These steps are currently taught by experienced supervisors using traditional teaching techniques, such as Video presentation and photographs. With the help of the

VR HMD, it is possible to bring the learning outcomes to a more immersive virtual environment, transferring the current expertise from documents and human experts into a virtual environment.

In this paper, we propose an innovative VR-based LNG firefighting simulation system that could prepare the cadets for unexpected and rare situations such as fire due to leakage from the pipes. Implementation of the VR system allows not only to expose the cadets to a dangerous situation in a safe virtual environment but also to acquire, refresh, and assess the cadets' knowledge learnt from the traditional teaching materials or experts. The proposed system comes with a novel human factors evaluation on non-technical skills in the firefighting scenarios. To achieve the automated non-technical skill assessment, a competence model is proposed in the human factors evaluation. Based on this model, non-technical skills such as situation awareness, vigilance, and decision making can be assessed. The resulting application can further be replicated, deployed, and used at different locations at the same time with minimal costs regarding scalability. To obtain the feedback from cadets and trainers about the system, we also conducted a pilot experiment, where 6 trainees and 2 trainers were recruited. Questionnaires were given and used to collect user feedback towards the system.

The paper is constructed as follows. In Section II, review on related work such as VR-based firefighting training and system evaluation is done. In Section III, the VR system design and scenarios are described. Section IV presents the experiment and the corresponding hypothesis. Section V shows the results. Finally, Section VI concludes the paper.

II. Related Work

A. VR-based Firefighting Training Systems

In comparison to real-world training, VR-based firefighting training has the advantage in aspects of safety, reproductivity, and cost. Much research effort has been made to create realistic virtual environments for firefighting training. For example, Tate and Sibert [6] designed a virtual environment for shipboard firefighting training and mission rehearsal. HMD and 3D joystick were used as input devices for interaction with the environment. A firefighter command training virtual environment was designed in [7] to evaluate commanding officer trainees, who are responsible for coordinating a team of firefighters to dispatch the fire. In this system, the trainees should give commands to a team of virtual firefighters to extinguish the flame. A networked firefighters training system was developed by [8] to train firefighters to deal with crisis situations, where each computer controlled one or several avatars. Another team-based training simulator was proposed by Lee et. al [9]. The joystick was used to navigate through the environment and accomplish the mission. Cha et. al. [10] developed a fire training simulator based on a real-time processing pipeline, where precise computational fluid dynamics simulation was used to render various physical quantities, such as toxic gases, heat, smoke and flame. The simulator allows firefighting activities such as evacuation and rescue to be conducted.

However, these previous works were based on classic graphic and interaction techniques. The rapid development of VR technology nowadays with higher visual quality at lower costs has started to allow adoption in various industries. The enterprise VR training market is predicted to grow to US$6.3 billion in 2022. In 2016, VR for training has been explored, using the first generation of broadly available VR HMDs. In 2017 and 2018, applications started to evolve from a proof-of-concept stage to a professional level. Recent advancement in VR hardware has created new possibilities for firefighting training. For example, Jeon et. al. [11] surveyed 15 firefighters and concluded that existing VR training systems tend to simplify the real fire situation and lower the effectiveness of training. They then identified three core elements to design firefighting training systems: situation, user's psychology, and behaviour. A user study with 22 participants revealed a better user experience of their system than existing ones. Clifford et. al. [12] investigated the use of a multi-user and multi-sensory VR system for the purpose of aerial firefighting training. By comparing their system with real-world exercise, they did not find a significant difference in the stress level measured by Heart-Rate Variability (HRV).

B. Training System Evaluation

A training system can be evaluated in the following three aspects - usability, task performance, and cognitive states [13]. Normally, the usability test investigates the ease of use, satisfaction level, acceptance of the particular system via questionnaires or observations [13, 14]. For example, in the evaluation of a personalized mobile patient guide system, three experts observed subjects' attitudes and reactions to the system and then reported the evaluation results [14]. Moreover, the end-user satisfaction survey based on the Likert scales was always conducted at the end of the usability test to investigate user satisfaction level and acceptance [15]. The task performance is reflected in aspects of user learning, error rates, response speed, and completion time [16-21]. For example, the accuracy scores achieved by the trainees were used to evaluate an open-source online training system [19]. The task completion time and task accuracy scores were adopted in the evaluation of a three-dimensional radar display in air traffic management operations [16]. The cognitive states, such as stress, workload, and anxiety are normally considered in the evaluation [22-25]. For example, the subjective technical and anxiety scores were adopted to assess a new auditory orientation training system, which was developed for blind people using acoustic VR [22]. When talking about a VR-based training system, realism, presence, emotions felt during the experience are essential factors to be evaluated [11] and usually obtained by the form of surveys and interviews.

In this paper, we prepared questionnaires regarding the presence, realism, emotions invoked, etc. of the VR experience to get the user feedback towards the proposed system.

III. System Design and Implementation

A. VR Implementation

We developed and implemented a VR-based simulation system for training/assessing the cadets for LNG leak and subsequent firefighting scenarios. The application is built with Unity and uses the steam VR service to make it compatible with a variety of VR systems. The VR system used to develop and use the application is the HTC Vive Pro, which was chosen for its robustness, quality, and ease of use.

The system includes a menu that lets the trainers choose the mode (ship-to-ship mode or ship-to-shore mode) on the fly and input the name of the trainee for the documentation of the analysed performance. The performance of each training session is saved in a text file.

The virtual environment is created in a 1:1 scale and delivers a realistic impression of an actual LNG ship. A detailed and realistic environment as seen in Fig. 1 is a key contributor to the immersion of the trainees. It also includes ambient audio on the deck and specific audio sources that indicate certain states of the LNG transfer process such as the flow of LNG in the pipes.

Figure 1. LNG transfer platform in ship-to-shore scenario.

Since the interaction space available in VR is limited to the size of a small room, a method to artificially move around the ship is used. In the case of the scenario, the trainee has to move between the accommodation and the LNG transfer platform. Teleportation is the best practical method that provides artificial movement without inducing any kind of motion sickness. To trigger the teleportation, we looked at two methods, grabbing the door as a trigger to teleport or standing still on a marked area to teleport. Walking from the accommodation to the platform would take around 3 minutes in reality, therefore, we decided to use standing on a marked area for a certain amount of seconds as the trigger to give the trainee a sense of distance. This is especially perceptible when the fire is spreading towards the trainee and an instant trigger to safety would deliver a wrong sense of safety.

In the scenario, the trainee starts in the accommodation of the LNG tanker seen in Fig. 2, which has instructions on how to interact with objects in VR pasted to the wall in a form of posters. The accommodation also includes fire extinguishers and gives the trainee a safe and relaxing environment to get used to VR and understand how to use the fire extinguishers. The extinguishers require to be first armed by removing the safety pin, after which they are ready to be used. The spray time and range are limited as in reality. Other interactable objects are the radio for communication and the ESD button. All interactions have realistic haptic, visual, and audio feedback.

Figure 2. Accomodation.

B. Scenario Description

The system includes two scenarios of LNG leakage that happens during (1) ship-to-ship (Fig. 3); and (2) ship-to-shore (Fig. 1) transfer of LNG. The two scenarios share identical logic flow but differ in the visual background. In both scenarios, the trainee is taught (1) how to spot an un-ignited LNG vapor cloud; (2) how to respond to the leakage; and (3) how to carry out standard procedures in the case of emergency such as fire outbreak caused by LNG ignition.

Figure 3. Ship-to-Ship scenario.

Here, we describe the scenario of ship-to-shore LNG transfer. In the beginning, the trainee is positioned in the accommodation of the ship. Within this space, the trainee receives a briefing on the usage of the simulation system.

During the briefing, the trainee is free to explore the virtual world, and to familiarize himself with the use of controllers to interact with virtual objects such as walkie-talkie and fire extinguishers. When ready, the trainee can teleport to the deck of the ship, where the ship-to-shore transferal of LNG is ongoing. The trainee should perform inspection tasks as he would normally do on an actual ship and watch for any abnormality or emergency. At a random time, LNG leakage would start on a random pipe, which would develop into a vapor cloud and lead to fire, if not properly handled. The trainee is trained to spot the vapor cloud at the earliest time possible, act properly and prevent the subsequent disastrous outbreak of fire. Fig. 4 shows the scene when the trainee is on the deck of the ship carrying out inspection tasks.

Figure 4. Trainee is wearing a head-mounted VR display and holding a pair of controllers which act as virtual hands in the virtual world. The monitor mirrors the scene seen by the trainee via his VR HMD.

C. Non-technical Skills Assessment based on Competence Model

Non-technical skills are usually assessed by human experts. However, lack of manpower and possible bias could bring problems to the assessment. To enable an automated and objective non-technical skills evaluation, we proposed a competence model based on [26]. In this model, an assessment matrix for the targeted non-technical skills is pre-defined, which lists the critical tasks and the corresponding non-technical skills required for those tasks. The relations between the tasks and non-technical skills are obtained by interviews with the experts. The experts are asked to rate the relations with a score ranging from 0 to 9. Here, "0" refers to no relation or a non-technical skill is not required for a particular task and "9" refers to strong relation or a non-technical skill is essential in this task. To get a conclusion about the level of non-technical skills, a performance score of each task is needed, which could be derived by behavior data or even biosignals recorded during the tasks. In this study, we use the behavior data output by VR such as reaction time, decisions made towards demanding events to calculate the performance score. By computing the sum of product between the pre-defined relation coefficients and performance scores, a final non-technical skills capability score can be obtained. In this study, the non-technical skills including situation awareness, vigilance, decision making are targeted to be assessed and the assessment matrix is constructed as shown in Fig. 5.

		Non-technical skills		
Task	Performance score	NTS_1 (Situation awareness)	NTS_2 (Vigilance)	NTS_3 (Decision making)
Observe the environment				
Detect the leakage				
Press the emergency button				
Evacuate				

Competence scores $=\sum_1^t W_t R_{tj} * P_t$

Figure 5. Competence model.

IV. EXPERIMENT

To investigate the user experience of the proposed VR system, we designed and carried out an experiment.

A. Subjects

Six participants, between the ages of 26 to 33, were recruited for the experiment. The participants consist of 6 males and they have no background in using VR training systems but 3 of them had experience in playing 3D games. Two trainers, who are lecturers with teaching experience and responsible for assessing cadets in the exams, were involved in the experiment to assess the trainees' performance in VR.

B. Experiment procedure

The experiment lasted around 25 minutes and the detailed procedure is presented in Table I.

Table I. Experiment procedure.

Time elapsed	Duration (mins)	Activity	Purpose
0h 00m	5	Trainee arrival	VR Equipment to be prepared and mounted on the trainee
0h 5m	5	VR environment familiarization	Introduction of activity to the trainee
0h 10m	5	Firefighting scenario	Conduct the experiment
0h 15m	10	Filling the questionnaires	Get the user feedback towards the system

C. Device

In the experiment, the HTC VIVE HMD was used. It has a resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels combined for both eyes), a refresh rate of 90 Hz, and a field of view of 110 degrees.

D. Questionnaires

A feedback questionnaire was designed and given to the trainees after they completed the task in VR. Questions regarding the presence, realism of the VR experience, emotions such as stress and fear induced during the simulation, attention paid during the experience were asked. A scale ranging from 1 to 9 was prepared for each question and the trainees to choose a value to indicate the intensity. For example, for the ratings about presence, 1 denotes that the subject had a strong sense of being in the real world while 9 denotes being in the virtual world during the VR experience. For the rating about realism, 1 means the scene felt real to the subject at no time while 9 means at all the time during the VR experience. For the rating of emotions such as fear and stress, 1 denotes the emotion is non-existent while 9 denotes the feeling of emotion experienced is very intensive. For the rating of attention paid to scene and sound during the VR simulation, 1 means the VR scenario did not catch any attention at all while 9 means the subject paid full attention.

E. Hypothesis

The data collected from this experiment are targeted to validate the hypothesis below.

H1: It is hypothesized that the users feel the presence of the real world during the VR experience.

H2: It is hypothesized that the VR experience brings a realistic scene to the users.

H3: It is hypothesized that the VR experience elicits similar emotions (such as fear, stress) in the demanding events as in the real world.

H4: It is hypothesized that the attention of the users is caught by the VR experience.

V. RESULTS AND DISCUSSION

The ratings from the questionnaires are analyzed and the results are used to validate the hypothesis in Section IV, E.

The average rating of the presence of reality is 7.2 which indicates that most of the subjects still felt they were in the virtual world during the VR experience. The boxplot of the ratings is presented in Fig. 6. Five out of the six subjects gave ratings equal to or greater than 5. Thus hypothesis 1 is rejected. However, the subjects also rated that the scene felt real to them with an average rating of 7.3 and the boxplot of the ratings is presented in Fig. 7. Here five out of the six subjects gave ratings equal to or greater than 7 and only Subject 2 gave a rating of 4. As a result, hypothesis 2 is confirmed. The feelings of stress induced by the gas leakage and fire outbreak are rated as 7.2 and 6.5, whereas the fear induced by the gas leakage and fire outbreak are both 6.8 on average. From the results, we can conclude that the VR experience evoked similar emotions in the demanding events as in the real world since it is supposed to feel stressed and frightened during gas leakage and fire outbreak. The boxplots for ratings of stress and fear encountered during the VR experience are presented in Fig. 8 and 9 respectively. All subjects gave ratings equal to or greater than 5 for stress and fear. Thus, H3 is confirmed. The average ratings for the attention paid to the scene and sound during the experience are 7.8 and 6.7 respectively, which may indicate that the subjects tend to pay more attention to the scene rather than the sound but generally they were attentive in VR. The boxplot is shown in Fig. 10. All subjects gave ratings equal to or greater than 5 for the attention paid during VR except Subject 2 rated 4 when being asked about the attention paid to sound. Thus, H4 is confirmed.

From the comments collected, positive feedback from the trainees includes "the visual is sharp and engaging", "the program is very good using VR experience" It is interesting to find out that Subject 2 who gave relatively lower ratings in the questionnaire stated that the VR experience was hard and he needed more time to get familiar with the VR environment.

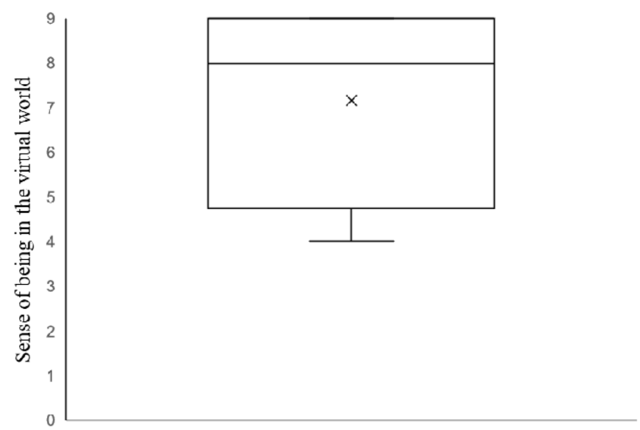

Figure 6. The ratings for the presence of the VR experience.

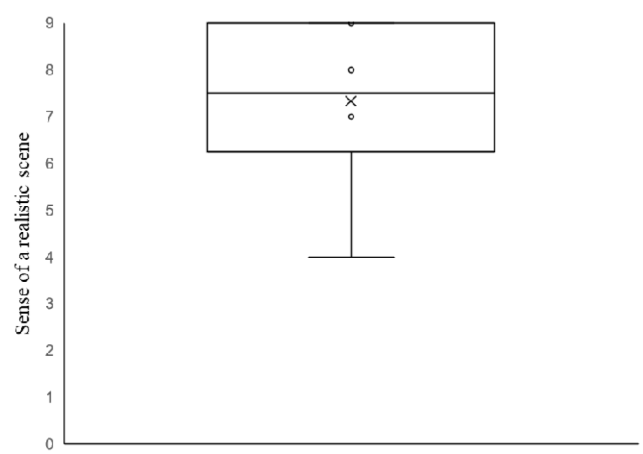

Figure 7. The ratings for the realism of the VR experience.

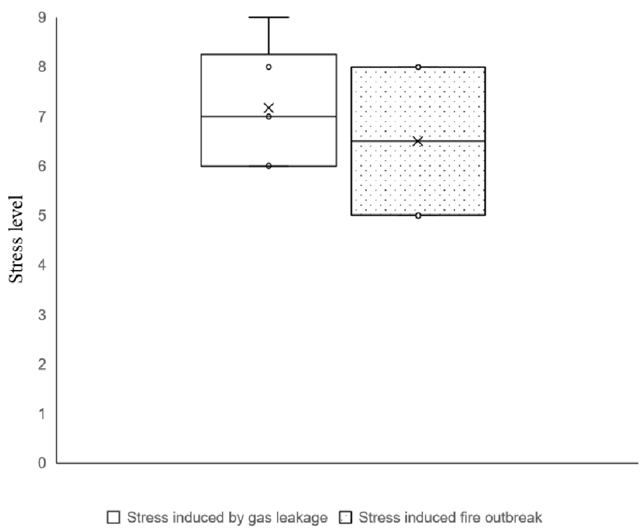

Figure 8. The ratings for stress induced by the VR experience.

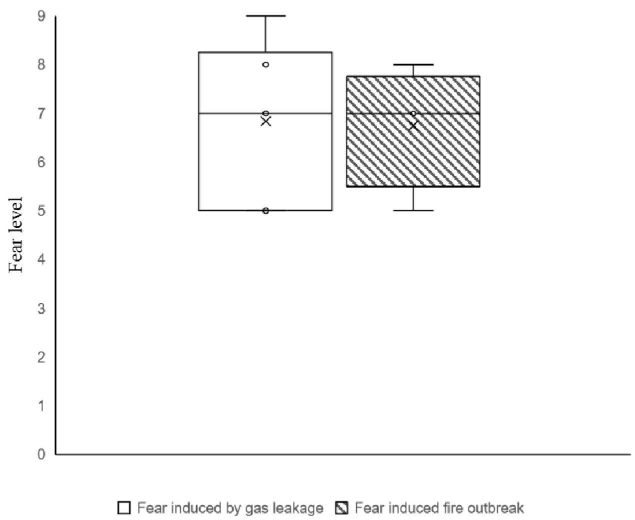

Figure 9. The ratings for fear induced by the VR experience.

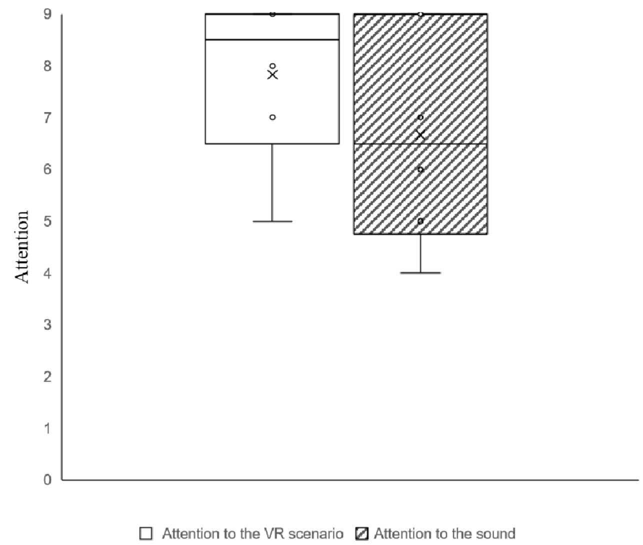

Figure 10. The ratings for attention caught by the VR experience.

VI. CONCLUSION

In this paper, we proposed and implemented a VR system for firefighting with human factors assessment. We designed and carried out an experiment to validate the usage of this system, where 6 cadets and 2 trainers participated in the data collection. The users' feedback on the system was obtained by questionnaires regarding the presence of the real world, realism of the VR experience, emotions induced, and attention paid during the experience. The results show that the maritime trainees felt the VR scene was realistic to them, evoked similar emotions (such as fear, stress) in the demanding events as in the real world and made them attentive during the experience.

The proposed VR simulation system will be used for training and assessing human performance with the unique human factors evaluation features to prevent accidents from happening in real life. As VR HMD is used in the proposed system, it can be easily used at different locations.

Currently, this system implementation is limited to one scenario of fast-spreading fire. In the future, more firefighting system scenarios will be implemented.

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