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Review

Application of VR Technology for Maritime Firefighting and Evacuation Training—A Review

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Abstract: Firefighting and evacuation training are important tasks in maritime education and training, especially for crews working on large passenger ships, to ensure the safety of the vessel, cargo and passengers. With the evolution of virtual reality (VR) technology and the introduction of wearable hardware, a change in paradigm has happened in firefighting and evacuation training where these new technologies are being introduced. This paper serves as a review on the use of VR technology in maritime firefighting and evacuation training, trying to answer the following questions: what is the current state of using VR technology, and what are the research gaps that need to be addressed to further accelerate the implementation of VR? Research shows that other industries have adopted the use of VR technology relatively quickly, but the maritime industry still seems reluctant. As for the research gaps, the physics-based modelling of fire spread is discussed along with two other topics: the lack of immersive solutions for evacuation and the potential for developing search and rescue scenarios onboard a ship.

Keywords: virtual reality; firefighting; evacuation; maritime education and training; passenger ship

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1. Introduction

Fire on a ship represents a serious threat to the crew, passengers, cargo and ship itself. The economic losses can be immense—according to the marine industry market analysis of nearly a quarter of a million insurance claims between 2017 and 2021, the top cause of loss is fire and explosion with an 18% share [1], as shown in Figure 1. An analysis of injuries occurring on ships according to the casualty event type in Europe [2] showed that in the same period, fire and explosion was the fourth most frequent cause of casualties with 59 cases.

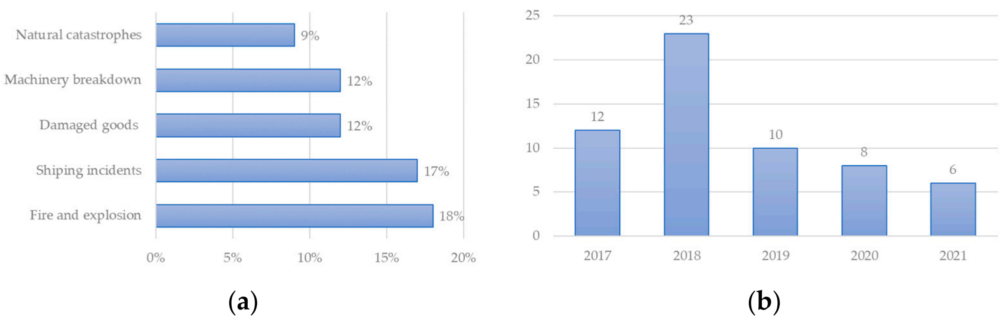
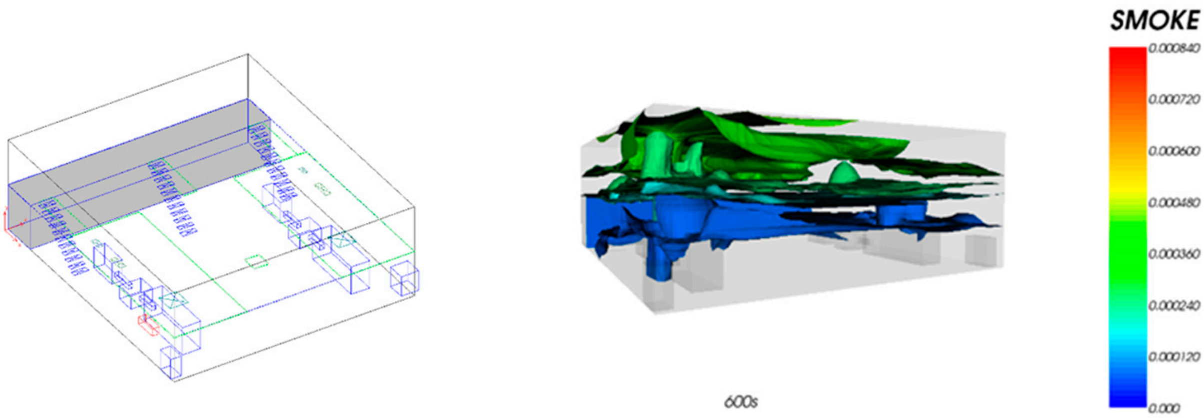


Figure 1. (**a**) Top causes of loss by value claims in marine industry, based on data from the Allianz Global Corporate and Specialty Safety and Shipping Review 2023 [1]. (**b**) Evolution of injuries in occurrences with ships, based on data from the European Maritime Safety Agency Annual Overview of Marine Casualties and Incidents 2022 [2].

In order to mitigate such fatal scenarios, ship owners and operators, among other measures, invest in the continuous firefighting and evacuation capabilities of crews. The principles of firefighting training are governed by the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) [3] adopted by the International Maritime Organization (IMO), who also issued the Guidelines on Evacuation Analysis for New and Existing Passenger Ships [4]. To be able to create credible firefighting and evacuation scenarios, there must be some understanding of fire dynamics and human behavior.

Until quite recently, this understanding came mostly from historical case studies of fires and emergencies on board [5–7], analytical calculations [8] or certain experiments that had to be of a limited manner to ensure the safety of the participants [9–11]. In the last couple of decades, with the introduction of advanced numerical routines and the rise of powerful computers, fire spread scenarios can be simulated using computational fluid dynamics (CFD), as shown in Figure 2. The CFD fire spread analysis has been proven as an acceptable tool during early-stage ship design [12] or a risk assessment tool for ship systems prone to fire and explosion, like engine rooms [13] or LNG tanks [14]. Furthermore, CFD fire dynamics analysis was coupled with evacuation models to build an integrated method for assessing passenger evacuation performance in ship fires [15]. Following a similar idea, an algorithm was derived that considers the interaction between the CFD model of the LNG gas spill and a crew evacuating on a floating LNG bunkering terminal [16].

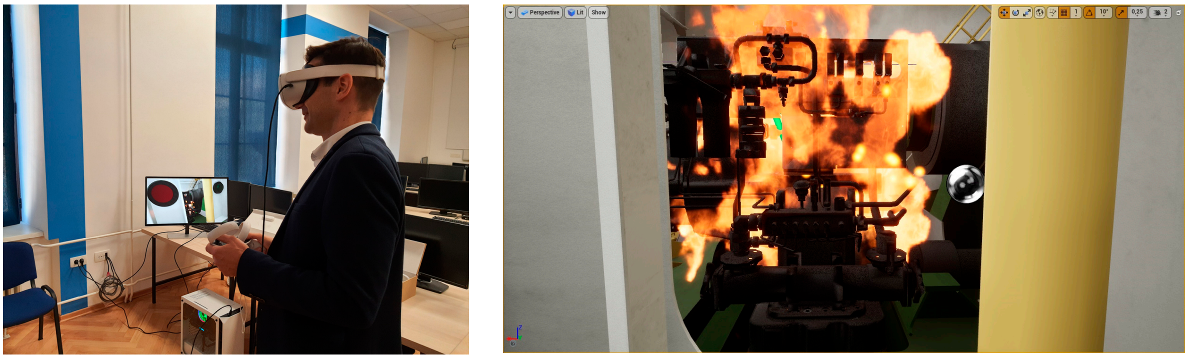


(a) (b)

Figure 2. Fire in an engine room modelled in SMARTFIRE v5.1 software. (**a**) A 3D sketch of the engine room with dimensions of 16.1 × 19.6 m. (**b**) Smoke concentration after 600 s. Both images are the own work of the authors.

Regarding the numerical simulation of evacuation, several models have been developed by scientists focused on human pedestrian behavior. One of the most frequently used are cellular automata models [17] or agent-based models [18]. Successful results have also been obtained using CFD models adjusted for pedestrians [19,20] and the recent multi-granularity quality function deployment model [21]. There is also a line of research developing risk models for the evacuation processes of passengers on cruise ships [22,23]. A general overview of these and other models used for simulating evacuation on passenger ships is given in two recent review papers [24,25].

However, these pure numerical methods showed some weaknesses. The first is that the numerically obtained results need to be verified in some way, preferably experimental, to be credible. Another is that the obtained results are hard to visualize for the average user, which is especially true for fire spread scenarios. This is where the novel concept, virtual reality (VR), has come into use, primarily in the last decade. Costly experiments and limitations of numerical analyses could be overcome by studying firefighting and evacuation problems using VR, which is a term referring to the fully immersive experience where the user is placed into a fully virtual environment made of digitally created objects and disabling the user from perceiving real surroundings [26]. Virtual content is typically shown via stereoscopic displays coming in the form of wearable hardware, large screens or wall projections, as shown in Figure 3. This technology was adopted early for firefighting and evacuation-training processes using game engines to develop immersive 3D environments struck by fires [27]. Since then, it has been used successfully for fire evacuation training in buildings and urban spaces [28–30], but it is yet to make an impact in the maritime sector.



(**a**) (**b**)

Figure 3. (**a**) User with a VR headset and a VR ship engine room displayed simultaneously on a monitor. (**b**) Image of an engine fire inside the VR environment. Both images are the own work of the authors.

VR is a part of the extended reality (XR) concept that incorporates augmented reality (AR) and mixed reality (MR), but it also covers the areas between them [31]. In AR, just part of the content the user is experiencing is virtual; thus, they can view the real surroundings, on top of which virtual elements are superimposed or blended in. AR, in comparison to VR, offers the user a closer experience of the real environment because it enhances the physical real-world environment rather than constructing a computer-generated virtual world [32]. MR merges the real and virtual worlds, producing new environments where physical and digital objects co-exist and interact in real time. In MR, virtual objects can be placed into a real environment or real objects can be incorporated into a virtual world to various extents [31]. In the research of pedestrian evacuation, the use of AR and MR is still limited [33], mostly due to ongoing development of partly immersive headware and challenges in the GPS tracking of users and recognition of surroundings.

Given this short introduction, some questions regarding the use of VR in the maritime field arise:

- What is the current state of using VR technology for maritime firefighting and evacuation training?
- What are the research gaps that need to be addressed to further accelerate the implementation of VR for maritime firefighting and evacuation training?

This paper tries to answer these questions through a comprehensive literature review on the matter. The review is focused on the problem of the firefighting and evacuation training of the ship crew.

2. Methods

The literature review presented in this paper follows four major steps [34]: acquisition of material, descriptive analysis, selection of category and evaluation of material, as shown in Figure 4.

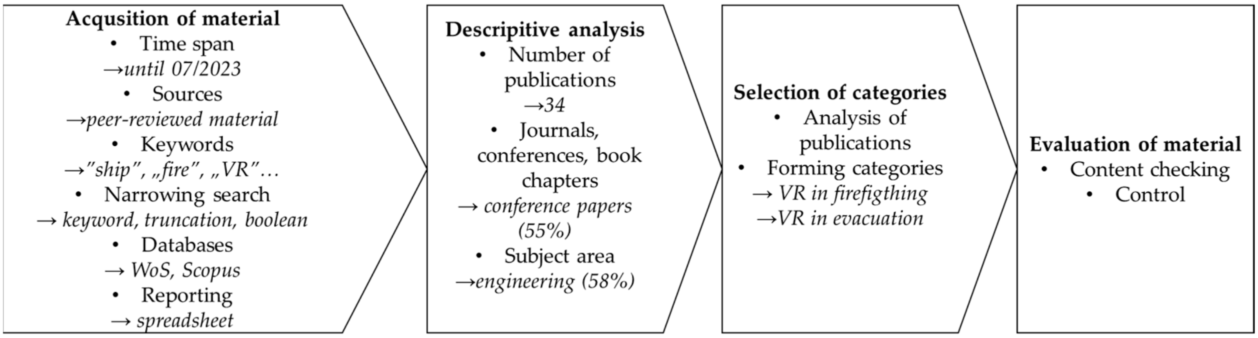


Figure 4. Four steps of the performed literature review.

The acquisition of material was carried out from January to July 2023. The following strategy has been adopted for the acquisition of material.

- Defining time span: all references available in the selected databases published up until July 2023 have been considered.
- Selecting sources: the authors opted to review peer-reviewed material consisting of available journal and conference papers, as well as book chapters.
- Identifying keywords: the keywords used to search for relevant literature were "ship", "fire", "firefighting", "passenger", "evacuation", "virtual reality" and "VR".
- Narrowing search: combination of keywords, truncation symbol (keyword root and asterisk sign), and Boolean operators was used to narrow the search among titles, keywords, and abstracts.
- Selection of databases: Web of Science (WoS), Scopus and Google Scholar were considered, but the latter was omitted due to significant number of non-academic publications [35].
- Reporting: the selected set of references has been organized in Excel sheets and the associated data used for subsequent visualization.

Papers not matching the aforementioned criteria were not included in the review.

Descriptive analysis showed that 34 journal and conference papers in total were found. The relative scarcity of publications may go in favor of the statement that the maritime sector is traditionally reluctant to adopt changes and implement novel technologies [36]. Also, it could imply that the topic is worth investigating, especially if the distribution of results is biased towards the recent dates. Most of the papers were published in conference proceedings (including book chapters as a result of a conference paper)—55%, while the rest were published in journals. It should be noted here that the application of VR is currently being investigated in another important aspect of maritime safety: that is, safe navigation [37]. The majority of the papers dealing with VR in the maritime domain, but not focused on firefighting and evacuation, deal with the navigational aspect [9,38–40]. This is especially true with the current introduction of autonomous ships [41–43].

Further in the descriptive analysis, the subject areas of publications were identified using the WoS and Scopus subject area identification feature, as shown in Figure 5. Most of the publications fell within Engineering (58%), followed by Computers (30%). Subject areas are important because they identify the dominant profile of scientists dealing with specific topics and can also help them to locate profiles complementary to their research. This is especially important in the multidisciplinary domain of the maritime industry where engineering, management, law and medicine work together on closely related subjects.

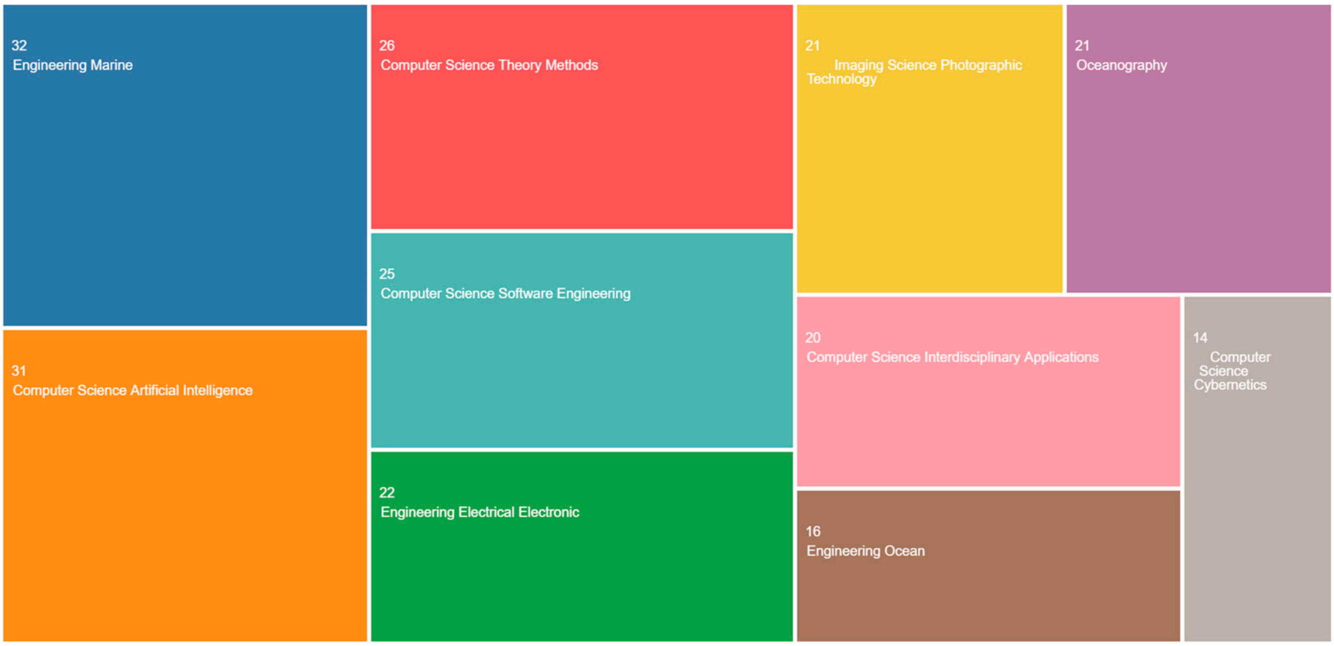


Figure 5. Example of subject areas distribution for papers acquired through Web of Science for a broad field of VR in the maritime industry.

The selection of categories for reviewed publications was performed in order to classify and group them according to their attributes. When taking the focus of each study into consideration, it can be concluded that the papers fall within one of two main categories: VR in maritime evacuation (64% of the published papers), and VR in maritime firefighting (36%).

Further, all studies incorporate numerical modelling and simulation to reach their results, which is expected given the topic of this review. However, some of the studies additionally use analytical (12%) or experimental (10%) methods.

What should be noted is, although the reviewed papers all deal with the use of virtual reality technology, the level of user immersion is not equal. There is a significant portion of studies that developed virtual reality of the ship environment but without the immersion of the user through wearable technology [38]. These studies mainly rely on the "classical" use of virtual reality, where the user controls virtual avatars using desktop accessories like a computer keyboard, mouse or touchscreen. Most of the recent studies, however, rely on using wearable technology to offer the full immersion of the user into virtual reality.

When making a selection according to the type of hazard, it can be noted that a significant number of papers dealing with evacuation problems disregard the type of hazard causing the evacuation (45%).

The evaluation of material followed as the last step. The selected papers were checked based on the initial reading of their abstracts and conclusion sections to detect possible discrepancies with the objective of this review. The aim was to ensure an improvement in the validity of the literature review and to limit the dissipation of the authors' focus.

3. Results of Literature Review

The literature review is divided into two main topics that follow in this section: the use of VR in maritime firefighting training and the use of VR in maritime evacuation training. Within 34 papers selected for the review, the focus is put on original studies, not reviews or technical notes.

3.1. Use of VR in Maritime Firefighting Training

One of the examples of the use of VR technology is a study of a ship firefighting training system [44]. Here, fixed water and carbon dioxide fire extinguishment systems were developed, and the user can control the virtual avatar using the Inverse Kinematics method. Researchers managed to nebulize fire and carbon dioxide using a particle system. According to the authors, experimental VR training showed favorable effects, but no evidence for that statement has been produced in the paper. A VR environment of a ship deck was developed using the Unity 3D game engine, a popular software framework designed for the development of video games [45]. The extension of this study by the same group of authors, however, offered a fully immersive experience of the firefighting training on the ship using wearable technology [46]. Coming from the same Chinese institution is the VR ship life-saving training system [47]. This is one of the studies that, besides firefighting, offers the possibility to train rescue procedures, even in the multiplayer mode.

The same game engine was used to design a fire simulation training system of the inside of the ship [48]. The authors of the study paid attention to the training evaluation scheme considering four aspects: extinguishing effect, completion time, safe operation and searching for items and personnel. These four aspects were given different weights (25%, 20%, 20% and 25%, respectively) and proportionally calculated, giving the success rate of the training.

The control of avatars performing firefighting training onboard a ship is a key focus of another study [49] that used Unity 3D to build a VR environment of a ship deck. An explanation of the game engine's method of simulating fire was given. Unity 3D uses a particle system to simulate fire, simplifying the physical characteristics of fire. The engine controls the fire by controlling the size, shape and number of fire particles. The initial state of the fire must be defined, along with the speed of fire spread and the time limit to extinguish the fire.

Researchers from the UK and Finland have introduced a virtual training technology called Immersive Safe Oceans [36,50]. With this fully immersive VR technology, four maritime safety training episodes were introduced with one being an electric cabin fire simulation. The objective of the fire episode is to assess the behavior of the trainee who should perform a series of predefined actions: press the fire alarm button, pick up the fire extinguisher, release the pin, check whether the door is hot, squat down to avoid breathing smoke, extinguish the fire efficiently, close the sliding fire door and move to the exit.

A fully immersive firefighting scenario of a fire in a ship's kitchen cabinet was developed for the Belgian Navy [51]. A VR environment was built using the Unreal game engine. The research team noticed several important aspects: when simulating fire and smoke, typical VR applications use a particle system, but the problem is that these particle systems often do not interact with one another. Additionally, smoke build-up provides the largest impact on the graphical processing unit (GPU) performance drop. The second largest impact on the GPU performance was the extensive use of draw calls to the graphics API to draw objects. A certain amount of relief for GPU could, however, be provided by reducing the number of 3D object polygons without significantly impacting the visual detail.

German authors have developed a firefighting scenario based on a real case of fire on the deck of the container ship Yantian Express in 2019 [52]. The size of the ship was the limiting factor forcing researchers to simulate separate gangways between the bays of the containers on the ship. The VR environment is built in the Unity 3D engine, and the application offers the possibility of multi-role training with some advanced controllers in the shape of water guns.

An Indonesian team have developed an Android VR application for inspectors of firefighting equipment [53]. The application works in two modes; one being a ship tour mode that gives the user a chance to explore the ship environment and introduces him to the firefighting equipment, and another being an inspection mode in which the user needs to finish a time-limited mission to locate the firefighting equipment and fill the inspection checklist.

Finally, in 2022, a ship firefighting training simulator with physics-based smoke was developed [54]. A purely Lagrangian vortex dynamics framework was proposed to simulate smoke and flame using velocity and vorticity fields discretized on discrete vortex segments. The main components of the framework include a stable geometric stretching solution and a particle strength exchange method. This is an advancement from previous research where the fire dynamics were simulated using only tools built in game engines. The reached simulation results show an improved fire-spread realism.

Table 1 summarizes the findings in this section.

Table 1. Specific features of VR solutions for maritime firefighting training.

Paper	Type of VR Solution	Fire Spread Modelled in	Learning Effect Studied	Game Engine
[44]	Non-immersive	Game engine	No	Unity 3D
[46]	Immersive	Game engine	No	Unity 3D
[47]	Non-immersive	Game engine	Yes	Unity 3D
[48]	Non-immersive	Game engine	No	Unity 3D
[49]	Non-immersive	Game engine	No	Unity 3D
[36]	Immersive	Game engine	Yes	N/A
[50]	Immersive	Game engine	No	N/A
[51]	Immersive	Game engine	No	Unreal
[52]	Immersive	Game engine	No	Unity 3D
[53]	Immersive	N/A	Yes	Unity 3D
[54]	Immersive	CFD	No	Unity 3D

3.2. Use of VR in Maritime Evacuation Training

As mentioned in the previous section, some studies do not incorporate full immersion of the user into virtual reality but offer a desktop experience of playing a "serious game" [55]. This is especially true for earlier studies, situated in a period when the development of wearable technology was not on today's level. A decade ago, a series of papers was published on the Virtual Environment for Life on Ships ("VELOS")—a VR platform for the analysis of ship evacuation [56–59]. VELOS presented a non-immersive VR environment where the user could control the behavior of virtual avatars with desktop accessories like a computer keyboard or a mouse. Features included the capability of introducing multiple users, real-time alterations of the environment and behavior, and analysis conducted according to the IMO rules. The calculated trajectories of avatars could be used in postprocessing for assessing the evacuation process. Several evacuation test cases due to fire onboard were developed within VELOS to test its functionality.

The concept of a serious game was used in the development of a prototype multiplayer Ship Evacuation Simulator (SES) [60]. It is a game that allows simultaneous participation of computer-controlled bots and human-controlled avatars in ship evacuation scenarios. Other causes of evacuation on a ship, besides fire, are considered.

An Italian group of researchers presented a validated agent-based evacuation simulation tool [61,62] placed in a non-immersive virtual reality, based on a social force modelling technique. The tool is verified and validated by referring to the IMO test cases, but what makes it interesting is coupling it with CFD fire simulation results to capture the actual response to the hazard.

Several research groups have used evacuation modelling as a tool for reaching an improved ship design that would allow for quicker and safer evacuation of the crew and passengers. The agent-based software "EXODUS" was developed to simulate crowd behavior in a 3D environment and, later, a special version "maritimeEXODUS" was created for the easier simulation of passenger movement on ships [63]. The postprocessing virtual reality animation tool allowed for the easier following of moving avatars on multiple decks of passenger ships. The software maritimeEXODUS was recently coupled with "SMARTFIRE", CFD fire simulation software, and a 3D naval platform model to form the Naval Damage Incident Recoverability Toolset (NavDIRecT) with the aim of facilitating the analysis of the crew interaction with damage events. The developed toolset can equally be used in merchant and commercial shipping [64].

"AENEAS" and "EVI" multi-agent non-immersive virtual reality evacuation software were used to calculate the evacuation times for a mixed population of passengers in different sections of a cruise ship. The results showed that potential congestion zones during evacuation could be used for improvement of the cruise ship deck layout [65]. EVI was also used as a tool to perform improved evacuation analysis in the verification stage of designing cruise ships, ferries and offshore construction vessels [66].

Table 2 summarizes the findings in this section.

Table 2. Specific features of VR solutions for maritime evacuation training.

Paper	Type of VR Solution	Modelling	Learning Effect Studied
[56–59]	Non-immersive	Agent-based	No
[60]	Non-immersive	Agent-based	No
[61,62]	Non-immersive	Agent-based	No
[63,64]	Non-immersive	Agent-based	No
[65]	Non-immersive	Agent-based	No
[66]	Non-immersive	Agent-based	No

4. Discussion

This section marks the noticed research gaps and tries to highlight possible future research directions in the use of VR in maritime firefighting and evacuation.

4.1. Advanced Modelling of Fire Spread in VR

When reviewing papers dealing with the application of VR in maritime firefighting training, one thing that was quickly noticed was that in most of the studies (except one [54]) fire was modelled inside the used game engine, most often by the particle system method. Although this "gaming" approach gives vivid flames inside the VR environment, it does not rely on evidence-based fluid dynamics. The most frequent case in the VR firefighting scenarios is that the fire is modelled as rather rudimentary and stationary, giving the user the time to recuperate after the initial shock and prepare himself for firefighting duty. These gaming scenarios are not founded on some kind of physics model that would predict the spread of temperature and smoke within the environment, thus forcing the user to adapt to the changing state of the fire front. The simulation of fire dynamics is generally left to the VR developers and, generally, there is a lack of evidence-based fire modelling in the virtual reality environment. While that may not pose a threat to the integrity of firefighting and evacuation scenarios on low-scale applications (e.g., for training of a general audience), for VR applications intended to be used by professionals this is a significant feature that needs to be addressed. This is especially important for the maritime industry where the crew, who are often the first and only responders to a fire, need to be highly trained for their firefighting roles on the ship.

This challenge could be approached by coupling the VR with the CFD. CFD tools can be used to model the origin of the fire and the subsequent fire spread, i.e., the change in temperature and the smoke growth. Based on these results, fire dynamics could be simulated in virtual reality. That way, users would receive a more realistic experience of the fire spread, enabling advanced firefighting and evacuation training.

A step in that direction was made by a group of Chinese researchers who developed a virtual-reality-based fire training simulator integrated with fire dynamics data [67]. The study proposed a series of data conversion techniques and a real-time processing framework to develop a fire training simulator based on CFD simulation capable of calculating physical quantities such as toxic gases, heat, smoke and flames. A similar concept of coupling CFD to VR was used to achieve the advanced simulation of airflow in a VR environment of a greenhouse [68]. Although not directly dealing with fire, the concept could probably be extended to problem of fire spread.

4.2. Lack of Immersive Solutions for Evacuation

Studies dealing with the application of VR in maritime evacuation training have been performed solely using non-immersive virtual reality technology. The used evacuation software is mostly agent-based, and the "virtual" part corresponds to a 3D visualization of the environment in which the evacuation is taking place. An additional feature of some of the studies is that the people in crowd are simulated using 3D avatars placed in the virtual 3D domain.

Still, no real immersive experience is offered here for users of the evacuation software. The pros and cons of virtual reality and augmented reality technology for evacuation training have been reviewed [69], and the observed weaknesses are the limited functionality of wearable hardware [70,71] and the need for powerful computer resources [72,73]. Wearable technology is taking giant steps forward every year and the level of graphical details in computer games is extremely high, but the computers cannot keep pace with this advancement. Playing a VR game (which evacuation training using VR would essentially be) is still very consuming regarding computer power. This is especially true for the multiplayer modes that should be used in evacuation training. Large-scale evacuation scenarios with people using VR technology are still likely to be on hold for a while.

4.3. Potential for Onboard Search and Rescue Scenarios

Approaches to the use of VR technology in safety training in the maritime industry are still limited to firefighting and, to some extent, evacuation. As stated in this section, one of the limiting factors is the capability of hardware resources to follow the demands of the gaming industry. This is true for large-scale evacuation scenarios.

However, this could be abridged by small-scale scenarios of search and rescue missions [74] onboard a ship. This type of drill is regularly performed by crew on ships [75]. Search and rescue scenarios usually involve a limited number of participants that should act accordingly. Given this, training participants could be placed physically in the same room to achieve better coordination. There is a problem of limiting their walking area in that situation, but that can be solved by them using omnidirectional VR treadmills.

5. Conclusions

This review aimed to answer two questions. The first was: what is the current state of using VR technology for maritime firefighting and evacuation training? As seen from the reviewed references, VR has been used relatively successfully for maritime firefighting training thus far, with most of the solutions offering a fully immersive experience. The Unity 3D engine is, by now, mostly used to develop virtual environments. Fire spread is mostly modelled using the built-in features of the selected game engine, but researchers are becoming aware of the need to build the fire model on physics and evidence-based solutions. As for the use of VR in maritime evacuation training, most of the solutions still rely on a non-immersive experience, where the VR is limited to desktops. This type of research raises interest among naval architects to develop improved and safer ship design, especially for the large passenger ships.

The second question was: what are the research gaps that need to be addressed to further accelerate the implementation of VR for maritime firefighting and evacuation training? As discussed in the previous section, the research gaps detected by the authors are: the possibility of the advanced modelling of fire spread in VR (modelling the fire spread in the virtual environment based on the fluid mechanics laws); developing fully immersive VR solutions for evacuation training (overcoming the problems of the needed computer resources, wearing headset limitations and multiplayer challenges) and the possibility of developing specific onboard search and rescue scenarios (helping diverse rescue teams in performing coordinated missions).

As technology continues to evolve, further research and development in this area holds the promise of even more advanced and effective VR-based training solutions, such as can be found in other industries. VR technology has, thus far, been successfully used to various extents in the emergency management of pedestrians in urban areas [76] and enclosed spaces [77]. Further, VR has been used to raise awareness of potential accidents in construction sites [78], train people in fire safety [79] or fire evacuation skills [80], and even emergency procedures in the case of earthquakes [81]. The maritime industry is waiting for this type of technology to be implemented widely in the process of ship design optimization, in the training of ship crew and passengers and in developing salvation scenarios for various types of accidents (e.g., grounding, collision, fire), ultimately contributing to a safer environment.

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