Design and development of a game-engine-based simulator specialised on ships evacuation

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Abstract: Modern ships have become larger in scale and function, and their complexity has increased considerably. This brings up many difficulties in evacuation and rescue when an emergency occurs. Therefore, effective evacuation and risk methods should be predicted and applied to design, safety training, and education. We have developed a three-dimensional ship evacuation simulator (SES) facilitating the impersonation of evacuees by computer-controlled autonomous bots (agents) that perform risk assessment and continuously calculate route conditions, communicate with neighbouring occupants, determine bottleneck points, and select the best evacuation routes. In this study, we introduce the simultaneous participation of human users and computer-controlled bots as evacuees in gamified multiplayer scenarios by the runtime spawning of 3D elements such as fire and smoke. SES is a game-engine-based simulator with several benefits such as flexible technology and economic feasibility. We believe that realistic and valid results can be obtained by applying SES in evacuation simulation.

Keywords: lightweight simulator; passenger ship; evacuation model; crowd simulation; human-computer interaction; virtual engineering; intelligent agent; evacuation simulation.

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1 Introduction

Cruise travel market stands on a rapid growth worldwide (Wang et al., 2019). In addition, due to several maritime disasters, passenger ship evacuation in case of emergency has received increasing attention recently (Stefanidis et al., 2019). It is essential to gain insight into factors like the evacuation time. Actually, the evacuation of large passenger ships like cruises is one of the most complex processes, since there are numerous people in the interior of an isolated, moving structure, over an unsafe medium, such as the sea water volume (Wang et al., 2014). Those factors transform the evacuation of a passenger ship, to a unique and individual evacuation subject, completely distinct and with numerous differences, compared to the evacuation of buildings or other structures and vehicles (Guarin et al., 2004).

Ship designers have to run several tests to check all the amendments and create the concept of ‘safe return to port’ (Vassalos et al., 2010). To do so, they can run an evacuation drill which is a planned evacuation scenario, with predefined rules and conditions, involving a number of volunteers, impersonating the evacuees. While evacuation drills may provide useful information and data, they are impractical and costly to run (Couasnon et al., 2019). The development of evacuation models and computer-based evacuation simulators arose from the inadequacy of evacuation drills because of their high cost, their poor repetitive capability and their easiness to cause accidents (Ren et al., 2006). Although an evacuation drill may provide useful information it lacks some basic elements. Drills, by their nature, cannot include and consider some significant factors such as the psychological pressure due to the stressful and hazardous conditions of an evacuation and moreover the social forces between the evacuees (e.g., parent-child relation, leader-following, herding) (Bryan, 1999). The panic reactions of the evacuees, the unexpected incidents that can happen during an emergency evacuation and the changes in the spatial characteristics of a ship’s structure can completely alter the output of an evacuation drill (Vorst, 2010; Wang et al., 2016). On top of that, the fire alarm systems (fire is the most common evacuation cause) have often failed to work ‘as planned' when a real fire breaks up because they were put in place with false expectations regarding how occupants actually behave during fires (Proulx, 2001).

Some of the above-mentioned factors can only be included in computerised evacuation simulators, where computer-controlled escapees evacuate a structure under specific rules and factors. Previous research uses simulations to track passengers during an emergency situation (Couasnon et al., 2019; Hu et al., 2019). But, while such applications can incorporate several features, such as the hazardous elements, the spatial characteristics and the evacuees' movement, they do not simulate human reactions based on the psychological pressure. Therefore, there is need of works that show how realistically the conditions of an emergency ship evacuation can be simulated by an application that can effectively collect output data of realistic evacuation scenarios (Nevalainen et al., 2015). Furthermore, previous works do not usually consider the three-dimensional (3D) perspective but in contrary are relied on two-dimensional environments (Ha et al., 2012). Moreover, works that combine artificial intelligence (AI) among with human users could alter the way we see evacuation scenarios (Kim et al., 2004). Finally, most ship simulation environments are either too complex or oversimplified, and only a few are freely distributed for community usage (Couasnon et al., 2019).

In order to annul these inconsistences, this work proposes a game engine-based ship evacuation simulator called SES. The basic idea of this work is to develop a 3D multiplayer simulator specialised on passenger-ship evacuation. In addition to that, we evaluate how capable SES is to reliably simulate evacuation scenarios, which involve large number of evacuees, hazardous elements and ship motion. The main motivation lies in the need to collect big amounts of data from ship evacuation simulations for future HCI research.

The SES environment is about a passenger ship and includes all the particular elements, that may exist in a passenger ship, such as listing, fire, fog, etc. The main idea behind SES is:

1 the improvement of the reliability of the simulation

2 the motivation of human users to act realistically, while they are immersed to the 3D virtual environment.

Elements such as the fire or the smoke are simulated and represented as 3D entities. Pre-define scenarios are created and executed, while there is the option to spawn events or elements in runtime. Human players coupled with computer-controlled bots participate as evacuees, attempting to escape the structure, pursuing clear goals and rewarded for their success, adding the necessary gamification elements and improving the realism. The results of every scenario are collected and can be reviewed and assessed further. The human behaviour under panic and during critical situations is implemented based on the assumptions by Keating (1982), Quarantelli (2001) and Santos and Aguirre (2004). These studies state that in contrast to the older beliefs, people in dangerous situations would not panic and would not be acting irrationally, as the popular culture has established. Instead, most people rationally, take logical decisions and tend to help others, whilst they attempt to save their lives and the lives of their family, friends and/or associates (Ribeiro et al., 2012).

Therefore, this paper researches how realistically the conditions of an emergency ship evacuation can be simulated by such an application and how capable is to collect the output data of evacuation scenarios. Finally, this work considers whether AI-controlled bots can act such as a human player should have acted, and in what degree and how runtime events (fire, fog, etc.) could alter the course of an evacuation scenario.

The rest of this paper is structured as follows: Section 2 presents previous works on SESs. The proposed simulator architecture and its basic features are described in Section 3. The two game modes (administrative and player mode) that SES offers are presented in Section 4. In Section 5, evacuation experiments are carried out and the fidelity of the simulator is examined. Section 6 discusses some considerations of the proposed simulator including limitations and future work. Lastly, Section 7 concludes the article.

2 Background work

Based on Law and Kelton (2000), a simulator is a computer software used to evaluate a model numerically and the gathered data is used in order to estimate the desired true characteristics of the model. As a result, the simulator imitates the operations of real-world facilities or processes and models the assumptions about the function of a system, based on mathematical or logical relationships. To this end, an evacuation simulator is a computer program that is assigned to imitate the process of evacuation incidents and produce results similar with the ones that a real-world evacuation would provide. Evacuation simulators are categorised by their basic features and capabilities and are focused on replicating various aspects of an evacuation incident. There are simulators modelling crowd movement, agent behaviour, spread of fire or smoke, etc. Previous simulation programs focus on various areas like:

- one floor buildings
- rooms
- multilevel buildings
- airports
- skyscrapers
- underground areas (metro stations, facilities)
- sea vessels.

The evacuation of a ship is a subject of extensive research since the beginning of the 20th century (Shiwakoti et al., 2009), due to the resulted high casualty's rates, its multifactorial and complex nature. Passenger ships are able to accommodate several thousands of people and for any review rule, it is crucial to define inspection objectives according to different stakeholders that are involved in the ship building process (Amirafshari et al., 2018). For example, the aim of a ship owner is to ensure that the system is made as good as possible, with minimum maintenance costs. Ship owners have the ships classed under classification societies that inspect them. Classification societies are NGO that establish and maintain technical standards for the ship building and operation. Ship designers, on the other hand, may feel that some rules are overly conventional and do not take into account the welding quality achieved. This means that they are required to do the same extent of inspection as a manufacturer with a reputation for less emphasis on welding quality. A SES can support these stakeholders and help ship designers to evaluate (early in the design process) passenger activities on a ship for different conditions of operations and to improve the design accordingly (Ginnis et al., 2015).

There are also essential regulations that are followed in ship construction and evacuation scenarios. The International Maritime Organization (IMO, 2016) has introduced a series of guidelines for undertaking complete evacuation analysis and certification of large passenger ships within the design stage. There is also SOLAS (International Convention for the Safety of Life at Sea (SOLAS), http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx), an international treaty that establishes minimum safety requirements for merchant ship building, facilities and service. Another important aspect for sea vessels is the jurisdiction under whose laws the vessel is registered (flag state) and the jurisdiction under the laws of the visiting port (port state). While, the flag state jurisdiction is mandatory, the port state jurisdiction is optional (Molenaar, 2007). A simulator can be used by the port and flag state authorities to verify if the ship holds the safety standards set by IMO or International Labor Organization (ILO), reducing the probability of refusal to the right of entry, based on safety issues.

Crowd simulation has always been a hot topic in computer graphics, cognitive science and AI, which combines mechanics, sociology, psychology and operations research and other disciplines. However, it is difficult to model the human perception and decision-making (Boulougouris and Papanikolaou, 2002). Simulating crowds in the virtual environment generated by a computer can provide great help to emergency responders and thus performs an important function in reducing the damage. The next subsections present the most commonly features of evacuation simulators.

2.1 *Characteristics of evacuation simulators*

Evacuation simulators models simulate the movement and behaviour of crowds. Kuligowski et al. (2005) propose a categorisation of evacuation simulators into three main types: behavioural-based, movement-based and partial-behavioural. These three categories imply the most prominently applied element of each model. A behavioural model is focused on the simulation of evacuee's behaviour while a movement on the simulation of evacuee's movement. Partial-behavioural models are primarily movement-based but behavioural elements are implemented during the evacuation sessions. The behavioural models are categorised further to no behaviour, implicit behaviour, conditional (or rule), AI and probabilistic models. The main movement models are the density correlation, the user's choice, the inter-person distance, the potential, the emptiness of next grid cell, the conditional, the functional analogy, the other model link, the acquiring knowledge, the unimpeded flow and the cellular automata (Kuligowski et al., 2005).

Each evacuation softwares implements movement capabilities for the agents and some of them enhance them with a certain degree of behaviour. Kuligowski et al. (2005) divided evacuation models into three major categories:

1. behavioural, that is referred to models that implement behaviour on the agents' movement
2. movement, that do not include behavioural aspect on the agents' movement

3 partial-behavioural, that combine the other two categories.

Moreover, there are several evacuation models, based on the implementation method of the of the agent's behaviour within a simulator. In the 'no behaviour' model, the agents have the ability to move but no behaviour is implemented on them. There is also the model of 'rule-based behaviour', which is implemented by:

1 enhancing the agents with personal characteristics that affect their reaction and movement

2 introducing incidents, environmental conditions

3 allowing the correlation and interaction between the agents.

Table 1 Agent's movement in a simulator

Proposed model	*Description*
Density correlation	Space's density defines the speed of a single agent or a group of agents.
User's choice	Speed, flow and density values are assigned by the user to certain spaces.
Inter-person distance	Each agent is surrounded by a 360° 'bubble' defining a certain minimum distance between other agents, obstacles, items and other components.
Potential	A grid cell in the space is assigned with a number value (potential). The agents move on the cells, while trying to lower their potential. The potential of the cells can be modified by the user, in order to indicate the attractiveness of an exit, the patience of the agent of the familiarity of the agent with the area.
Emptiness of next grid cell	A grid cell in the space is assigned. An agent will not move into a cell if this cell is occupied by another agent. The agent will wait, until the cell is emptied. If more than one, agents are waiting to occupy the same occupied cell, the model will resolve the conflict assigning which agent moves first.
Conditional	Conditional behavioural models define the movement of a single agent or a group of agents based on environmental, structural conditions, the correlation and the interaction with other agents. The model ignores much of the effect of congestion areas.
Functional analogy	Equations that define fluid movement or magnetism are assigned on certain areas, affecting the agents that enter them. The equations generally, are depended on the density of the space.
Acquiring knowledge	Focuses on the acquired knowledge during the evacuation process. It is consisted by the recognition of congestions, bottlenecks, etc. There is no real movement algorithm because evacuation time is not calculated.
Unimpeded flow	Unimpeded flow models calculate the unimpeded movement of the agents while add or subtract delays and improvement times to deduce the final evacuation time result.
Cellular automata	The agents move from a cell on a grid space to another cell by the simulated throw of a weighted die.

When a condition is triggered, the agents react accordingly. There is also the model of 'probabilistic behaviour' where many rule-based models are stochastic and the results are calculated by the continuous repetition of certain simulation sessions, which produce various outputs. Finally, there is the 'AI' model, in which the behaviour of the agents is simulated based on AI equations in order to mimic the reactions of real humans during evacuation events.

In most simulators, agents are initially set to specific unimpeded velocities and any changes are applied by the simulator when the agents enter congestion and queuing areas, where the agent are gathered and jammed due to the limited space and the high-density situation. The agents' movement can be also categorised, based on the agent's movement method as shown on Table 1.

2.2 User's participation and spatial perspective

Users' immersion is one of the key features of virtual environments, such as computer games or simulators. Brown and Cairns (2004) argue that in the stage of the 'total immersion', the user's senses are cut-off from the real world and only the end of the computer game is all that matters. The level of immersion is defined by the interest that a virtual world causes to the player, the permanent existence of tasks to complete and continuous update of challenges) and the feeling of flow, where people are completely absorbed in the activity (IJsselsteijn et al., 2007).

The majority of the evacuation software simulates the evacuation of computer-controlled agents – bots, enhanced with a behavioural algorithm. The only direct human intervention is the setting of evacuation rules before or during a simulation session (for example the number of occupants, crowd composition, events, etc.). The participation of real users allows us to observe and assess the human behaviour and human crowd movement. During an evacuation session, the elements of human behaviour that can be observed are:

1 the under-stressful conditions behaviour

2 initial response time

3 the path selection.

As an outcome of an evacuation simulation session, the alteration of egress time and casualties' rates due to human participation can be calculated. In addition, specific simulators can be used as a virtual training field for personnel, ship designers or rescue team members [e.g., VELOS (Ginnis et al., 2015)].

The main advantages of the 3D perspective are:

1 the participation of real players to the simulation process (either as evacuees or as administrators), for testing and/or for training purposes, which is impossible in two-dimensional simulators

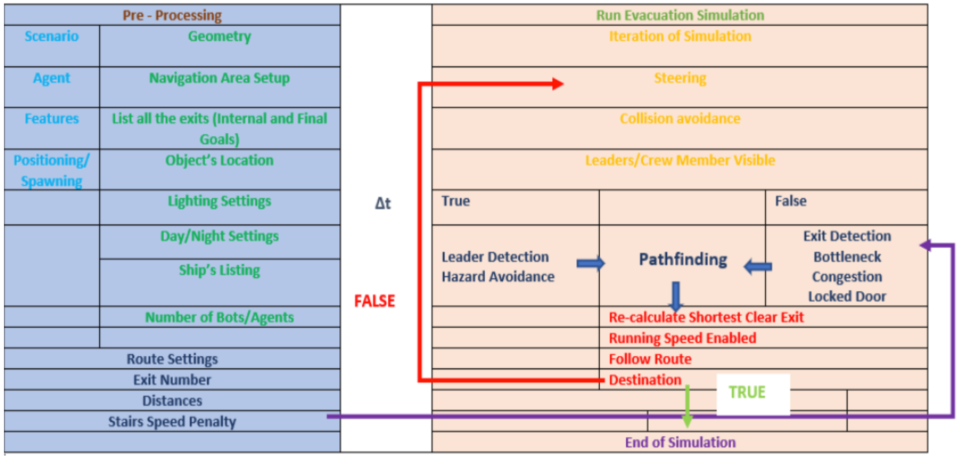
2 the real-time monitoring of spatial events, such as the bottlenecks and the counterflow.

Two-dimensional perspective is used, mainly, on earlier models of simulators. As the graphics technology and computer's capabilities improve, we notice that the latest models support 3D perspectives especially the ones that allow user participation on a virtual reality environment.

3 Software architecture

The basic idea of this work is to develop a lightweight simulator with a game engine, specialised on ship evacuation. The proposed simulator (SES) considers behavioural aspects and scenario modifications at the same time (Figure 1). These two aspects are identified, and interactions between them are described in order to take advantage of this agent-based approach (Helbing, 2012).

Figure 1 Process of evacuation simulation (see online version for colours)



SES provides a visualisation of a complete evacuation, detects bottlenecks and analyses evacuation routes. Moreover, SES could support specific techniques for the operative description of each single involved agent.

3.1 Simulation characteristics

The simulation aspect of the proposed application is reflected on the simulation of the following aspects:

- Ship's motion and its effect on the motion of the evacuees and the objects in the ship's interior.
- Internal illumination conditions.
- Breaking of fires, smoke and the spreading of poisonous gasses.
- The appearance of fog.
- Day/night conditions and illumination.
- The inlet of sea water.
- The spatial conditions in the ship's interior such as congestion and bottleneck areas.
- The motion and the behaviour of the human crowd and individual evacuees. While an evacuation session runs a number of (or all) the above-mentioned elements are triggered or spawned aspiring to simulate authentic evacuation conditions.

The evacuees are human-like models and controlled either by AI (called bots) or by human players (called avatars). User-players control their avatars-evacuees pursuing to survive and/or help other evacuees, while evacuating the ship. Bots are capable of dynamically recognising the optimum visible escape routes (dynamic routing redirection), following the optimum routes (optimum route following), following leaders, parent or crew members and imitating the social behaviour of other evacuees (bots or avatars).

3.2 Gamification elements

Deterding et al. (2011) argue that games are characterised by explicit rules systems and the competition or strife of actors towards discrete goals or outcome. Based on that assumption, we have implemented gamification element to SES, in order to assess their impact on the simulation. The proposed simulator is gamified since it integrates game mechanics to motivate participation, engagement and loyalty (Deterding, 2012; Hamari et al., 2014). More specifically, it implements antagonistic elements, conditions that contribute to the immersion of the user and clear pursuable by the user and rewarding goals.

SES, with regards of it, is categorised as a multiplayer action-role-playing simulator (MMO-ARPG). Multiplayer since a number of human players can join an evacuation session, survive, help others or just simply escape, controlling their avatars. Role-playing since the avatars come with fixed capabilities, strong and weak points based mainly on their age and sex. These capabilities may vary from the speed to the height of an avatar. This feature greatly improves the immersion level of the human players and the realism of the simulation, as the players feel that control a real human being. The action element contributes to the wholistic nature of the otherwise mindless avatars as the human users control their actions. Lastly, SES's gamification aspects are shown by the following factors:

- Human users are immersed to a virtual environment due to the realistic graphics, sounds and evacuation environment.
- There are clear goals for the human users in order to motivate them to participate to the simulations As Dubbels (2013) states: "by removing purpose, the player may abandon the game (or in our case the simulator) for lack of challenge", so we ensure that this would not happen during the simulation, continuously motivating and challenging the players.
- Moreover, there is a competitive environment and among the human players and the bots, with a clear ultimate goal to save their lives.
- The interactivity
    1. among the users
    2. among the users and the computer-controlled bots.

3.3 Game engine-based and 3D implementation

Two-dimensional simulators use dots or artefacts for the representation of the evacuees or any other elements such as a fire and smoke and viewers perspective is usually a top-down one. A 2D approach is not inferior than a 3D one, but its usability is restricted to specific functions and specifications. The evacuation models are functionally implemented, while the evacuees are rendered symbolically, while the simulation can be accelerated or decelerated according to the user settings. On the other hand, a 2D simulator cannot support the direct participation of a player impersonating an evacuee and therefore their unexpected behaviour. The computer-controlled bots do not always act as a human being rendering the collected data less reliable (Helbing et al., 2002). Improved and well-designed algorithms may control a bot towards realistic reactions and behaviours but can only simulate a small portion of the qualities and the unpredictable behaviour of a human being or a group of human beings. 3D simulators usually use 3D human models for the evacuees or any other roles (rescue team staff, crew members, etc.). The structures (e.g., buildings) are usually 3D models of existing structures further enhancing the realism and are more or less in a gaming environment. The importance of this approach, is based on the easiness and improvement of the understanding of human behaviour in evacuation situations, as the subjects are monitored while they are playing the game and some performance measures are logged to be further analysed later on (Ribeiro et al., 2012). Nygren (2007) proposes that a 3D evacuation simulator can combine the focus on the behaviour of individuals and the behaviour of crowd, as it allows the participation of real players simultaneously with computer-controlled bots.

Table 2 Basic game-engine features that were used in SES

UE4 game-engine features that were used in SES	Includes 3D rendering tool of textures, materials and objects.
	Provides UI design tools, suitable for the game menus and HUDs.
	Allows the implementation of the forces of nature (physics), such as gravity, friction, motion.
	Wraps physical boundaries (colliders) around virtual objects and characters, allowing them to physically interact with other objects or characters.
	Enhances bots with intelligence based on a build-in AI system (behaviour trees and blackboards).
	Implements exterior illumination and weather condition elements such as the sun's position or the appearance of fog.
	Implements internal or artificial illumination elements in the form of various types of light sources, such as point lights and spotlights.
	Allows the broadcasting of voices, announcement, alarms and any other sounds from sources such as speaker, evacuees or objects.
	Imports models developed using third-party software such as chairs, table and even evacuees.
	Provides the blueprint block scripting language and the C++ programming language.
	Provides networking tools, allowing the simultaneously participation of a large number of human users.

SES has been developed using modern technologies from the field of video games. The game engine used, was Unreal Engine 4 (UE4) which is ideal for the development of large and complicated projects such as an evacuation simulator. Its simplicity and extensive documentation, allows developers to contribute only a short period of time for the initial setup of the application since they can easily import graphic models from third party software, develop algorithms and simulate physics. Moreover, UE4 game engine provided all the important features and tools for the development of SES, as listed at Table 2.

Objects such as chairs, tables, drawers and doors, were designed using the 3D Studio Max (3DS Max: 3D Modeling and Rendering Software for Design Visualization, Games, and Animation, https://www.autodesk.com/products/3ds-max/overview). We chose this modelling software since it creates qualitative, fully functional 3D objects and sets their properties (such as the pivot point, centre of gravity), dimensions and surface friction) and adds colliders, setting the interaction rules between objects.

Finally, human characters (avatars) created with Mixamo Fuse 3D human character modelling application (Mixamo: Animated 3D Characters, https://www.mixamo.com). Mixamo was selected for the fast, qualitative and easy creation of exportable human models of any kind, race, sex and age (Figure 2). These models can be easily uploaded to Mixamo's webpage and be animated by picking animations from a considerable collection of animations, such as running, idling, swimming, falling, dying, etc.

Figure 2 A group of spawned evacuees (see online version for colours)

4 SES main features – user interface

SES offers two main game modes: administrative and player mode.

4.1 Administrative mode

In this mode, a user administrator can access and spawn all the elements and functions, of the simulator, while actively participating in the action spawning evacuees, setting the parameters and controlling the various elements of the simulation. The most important administrative features are listed in Table 3.

4.1.1 Game modes – evacuation scenarios

Moreover, the administrator can configure the initial parameters of the evacuation scenarios selecting among three game modes. The modes are to be selected based on the purpose of any individual evacuation simulation scenario. When one of the below listed game modes is chosen the initial simulation scenario configurations are set:

- *Simulation-only mode (SO):* This simulation mode allows exclusively bots (AI-controlled evacuees) as participants. An administrator can fly across the scene as an invisible and bodiless identity, spawning events, hazardous elements and even bots. This mode is ideal for the conduction and assessment of evacuation scenarios without the intervention of human users. It is proposed for the collection of data and its assessment, of real incidents, of alternative real scenarios and the continuous repetition of evacuation scenarios.

- *Single simulation mode (SiS):* This mode allows the administrator to participate as an evacuee (or crew/rescue team member on later updates) among AI-controlled bots. No further human participation is allowed. The administrator retains the ability to spawn events, elements and human characters. This mode is proposed for testing locations, elements and affected of the simulator without the intervention of other human users. It can also provide reliable simulation output.

- *Multiplayer simulation mode (MuS):* This mode allows the simultaneous participation of a large number of human users (controlling avatars) among with AI-controlled bots. This is a crucial element of SES, as it allows to assess the effect of the simultaneous participation of bots and humans in the same simulation scenario. It can also allow us to evaluate the degree of realism and the ability of the bots to learn and imitate the behaviour of real humans, while effectively evacuate the ship. The maximum number of human users and bots can be set during the configuration phase, but the administrator can increase the number of the participants (human users or bots) while the simulation is running. This mode is proposed for the assessment of the human behaviour during an evacuation, the evaluation of the simultaneous humans-bots participation and the assessment of the, in runtime, spawned effects (fire, smoke, etc.).

Table 3 SES administrative mode features

Administrative mode	Setting the simulation scenario and the initial properties of the simulation up. Initiating the evacuation by triggering an initial event such as spawning a fire or smoke. Spawning of any hazardous elements or triggering of event (e.g., ship's listing) in real-time after the initiation of the evacuation process. Observing the spatial phenomena such as bottlenecks and congestion areas, assessing the effect of counter flow, stairs and elevator on crowd's movement and behaviour, observing the behaviour of individual evacuees and the crowds, such as mimic, under panic, herding and stressful conditions behaviour, initial response time, leader-follow behaviour. A new update should include children and disable people behaviour. Collecting extracted simulation numerical data such as the death toll percentage, the death or injure causing elements, the total number of the escapees. Terminating the evacuation sessions.

4.1.2 Initial and runtime spawning

An administrator can setup some initial effects and elements while may continue spawning in runtime (Figure 3). The initial setting and spawning phase is implemented before an evacuation scenario starts. During this phase, an administrator creates a custom scenario based on the initial settings as shown at Table 4.

Table 4 Initial settings posed by administrator

Setting	*Description*	*Game mode*
AI bots	A number of AI-controlled bots. These bots are spawned at random locations, when the simulation scenario starts.	SO, SiS, MuS
Player's maximum number	The number of human users that can participate in a single scenario. This option is available on multiplayer mode only. An administrator can alter this number in order to test the crowd behaviour with various compositions.	MuS
Fire sources	The number of fire sources, the Intensity level which sets the size and the heat that the fire radiates. These fire sources are spawned at random locations, when the simulation scenario starts.	SO, SiS, MuS
Smoke sources	The number of smoke sources, the density level sets the size and the area that a smoke source occupies. These smoke sources are spawned at random.	SO, SiS, MuS
Poisonous gases	The number of poisonous gases starting points, the toxicity level sets the deadliness of the gas. These poisonous gases are spawned at random locations, when the simulation scenario starts.	SO, SiS, MuS
Waves intensity*	The yes and no option define the presence of rough see or not. The intensity option is going to be integrated later.	SO, SiS, MuS
Ship's list	The check button option defines the presence of listing or not. The starting slope (in degrees) feature is going to be implemented later. An administrator can control the listing angle and speed.	SO, SiS, MuS
Inlet of water*	This option defines the presence of rising water or not. The uprising can be set in cm per minute and the next option defines the water as frozen that hurts additionally the evacuees that come in contact with. This feature is going to be incorporated later.	SO, SiS, MuS
Illumination	An administrator can choose among the normal (normal ship artificial illumination), the alarm lights (red lights), the low lighting (low intensity of lights) or the no lights (the power is off and there is not artificial lighting in interior of the ship). The alteration of light conditions affects the bots too, as they are programmed to react such as a human being during low or no light conditions.	SO, SiS, MuS
Day/night	This setting defines the day period providing two possible options: day or night. The administrator can choose among daylight or night-time conditions.	SO, SiS, MuS
Fog	The option sets the heaviness of the fog around the ship. No fog options means no fog at all, light fog applies a light fog and heavy fog applies heavy fog conditions.	SO, SiS, MuS

Note: *Settings with an asterisk are going to be integrated in a future work.

Figure 3 Screenshot of the administrator's HUD (see online version for colours)

Select Spawn: Select a Spawn
Water Inlet
Set Ship Lights: Select Lights Condition
Set Period of Day: Day
Set Smoke Heaviness: No Additional Smoke
Set Sea Roughness: Calm
Set Fog Heaviness: No Fog
Number of Evacuated Persons: 0
Time: 0.35

Furthermore, the real-time spawning phase settings appear on the top of the Administrator HUD screen after the initiation of a simulation scenario. The administrator can spawn any element or event. This first effect could trigger the evacuation process if it is perceived by the users' senses (vision or hearing). As an example, a bot that can see a fire source needs some time to react (initial response time) and then notifies other bots, triggering an alarm and setting all the bots in evacuation mode. This phased can be activated by:

a spawning an element at an observable by the evacuees' location

b by triggering the ship list event where the ship begins to slope

c by triggering the alarm using the alarm button in the administrative HUD.

Moreover, runtime spawning allows the administrator to directly intervene in the simulation and affect the flow of the events. Any events that should be added after the initiation of a simulation session should be triggered during this phase, such as:

- *Select spawn type:* This scroll bar menu allows the administrator to select among fire, smoke, poisonous gas elements or female teen, female adult, female old, male teen, male adult, male old characters (evacuees) and to spawn them by clicking on specific locations.
- *Ship's list:* The same effect with the initial phase, but when is unchecked the ship's list stops in a specific angle.
- *Ship lights:* The same effect of the initial phase, but the light's conditions can be changed in real-time.
- *Day/night:* The same effect of the initial phase, but the option can be changed in real-time.

- *Waves intensity:* Same as of the initial phase.
- *Inlet of sea water:* Same as of the initial phase.
- *Fog:* The same effect as the initial phase, but the effect can be altered in real-time.

4.1.3 Observation

Administrators are also tasked with the recognition and observation of the spatial and behavioural phenomena. Phenomena of this type are hard to be recognised by the application itself and therefore we proposed to be observed and recognised by an administrative user with experience and knowledge on the concept of evacuation. Some examples of the above-mentioned phenomena can be found below:

- *Bottleneck:* A bottleneck denominates a limited area of reduced capacity or increased demand. Pedestrian movement bottlenecks are usually formed by direct capacity reduction (door or corridor). Bottlenecks are of fundamental importance in the calculation of evacuation times and other observables for buildings or structures (Kretz et al., 2006).
- *Congestion:* Wang et al. (2015) describe congestion areas such as situations that some agents want to move to the exit quickly by crowding other agents. Since under intense stress people try to move faster than normal, the overtaking and casualty phenomenon usually arise. This phenomenon is very common in emergency situations.
- *Counterflow:* As Yoshida et al. (2001) argue after the outbreak of a disaster, a number of people move against the main stream of evacuees toward their cabins or seats in order to search their relatives and gather their belongings, life jackets, etc. This causes a stream of movement directly opposing the main flow toward exits, that contributes negatively to the total evacuation time and overall evacuation conditions.
- *Climbing stairwells:* Encountering stair the evacuees reduce their speed, due to the higher effort needed to climb the stairs. The speed is kept being reduced for as long as they struggle to climb a stair moving upwards. The effect is not applied when the evacuees descent a stair.
- *Movement by elevators:* This feature is planned to be implemented later.
- *Behaviour under stressful conditions:* Helbing et al. (2002) and Pelechano et al. (2005) propose some observable behaviours commonly present during an evacuation. Behaviours such as mimic behaviour, leader-following, panicking, child-parent follow-up behaviours can be partially recognised by an administrator, while the output of those phenomena should be reflected into the extracted numerical data. As an example, if the children-evacuees are observed to follow their parent, then we expect lower casualties among this category of evacuees.

4.1.4 Output data collection

After the completion of an evacuation session the administrator can collect and assess numerical and statistical output data. The categories of this data are shown at Table 5.

Table 5 Numerical and statistical output

Output result	*Description*
Starting and spawned evacuees	The numerical representation of the spawned evacuees from the initial phase and the spawned evacuees during the real-time evacuation.
Evacuee's crowd composition	The numerical and percentage representation of the individual categories of evacuees. We display the categories of TM, AM, OM, TF, AF and OF.
Total safely evacuated	Indicates the total number of safely evacuated individuals and their percentage.
Safely evacuated by category	Indicates the number of safely evacuated individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF and OF.
Total casualties	Indicates the total number of deceased evacuees, individuals and their percentage.
Casualties by category	Indicates the number of deceased individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF and OF.
Total injured	Indicates the total number of injured evacuees, individuals and their percentage.
Injured by category	Indicates the number of injured individuals and their percentage by category. We display the categories of TM, AM, OM, TF, AF and OF.
Injured by injury cause	Indicates the number of injured individuals and their percentage by injury cause. We display the causes of fire, smoke, poisonous gas and other.
Exit selection	Indicates the percentage and the number of evacuees depending on their exit selection and category. E.g., side door A: total 10% and 10/100. Men 30% and 3/10 – women 70% and 7/10.
Evacuation time	Indicates the total evacuation time.

4.2 Player mode

The player mode is proposed for users or testers of the SES, impersonating virtual evacuees (avatars) during evacuation simulation sessions. The main purpose of those users is to escape the ship, while in critical and dangerous conditions (e.g., fires, smoke, listing). Moreover, a player may, optionally, assist other evacuees undertaking the role of the leader or the guide. The participation is not frequently met in evacuation simulation applications, therefore is considered as one of the most important and innovative features of the SES. The administrator recognises and assesses the actions of the users, while spawning ongoing events. The observed behaviours can be compared with previously collected data, from real evacuations or other simulators. This feature is purposed to assess the deviation of human behaviour under real-life stressful conditions. Another goal is to study the interactivity among human users and AI-controlled bots and to evaluate how realistic this interaction can be.

4.2.1 Evacuee type selection

The available evacuee types are teen male (TM), adult male (AM), old male (OM), teen female (TF), adult female (AF) and old female (OF). The users are prompted to pick one type and enter the game while they are encouraged to choose an evacuee that matches their age and gender increasing the realism. An OM user is expected to behave differently compared to a TF one, based on their different background and experiences. Additionally, taking into consideration Duncan et al. (2007) and Himann et al. (1988), aging directly affects the speed of a person. Subsequently, the avatars of different ages are applied with different median walking and running velocities. OF and OM types have the lower velocity (0.26–0.27 m/s). Female and male teens types are a bit faster mainly because of their shorter limbs (0.67–1.0 m/s). Finally, AF and male types are the fastest ones (1.27–1.34 m/s).

4.2.2 Spawning

An evacuee is spawned in a random location inside the ship. An evacuation:

1 initiates immediately

2 could be initiated when an evacuee detects an imminent hazard (fire, smoke, etc.)

3 initiates if the slope of the ship reaches a high level.

A user is able to hear sounds and voices, from sources close to him/her. How clear those sounds and voices are depended on how distant and how intense those sources are. The users can switch from third-person perspective to first-person perspective and reversely. A third-person perspective viewing point is set over the head of the avatar, while a first-person over the line of the eyes.

4.2.3 Player's HUD

The human users are provided with information on the condition of their avatar, via the player's HUD. Two indicators are listed below:

- *Health bar:* The health bar reflects the physical condition of the avatar. While a direct and prolonged contact with a hazardous element (fire, poisonous gas) should completely deplete this bar, an indirect and instantaneous one should reduce only a portion of it. This bar drops while the avatar is in contact of a fire source, is been inside a smoke source or a poisonous gas or it is hit by objects, such as chairs and tables. If the health bar drops under 50% the avatar is prevented from jumping and running, while its walking speed is significantly decreased. If the health bar reaches 0%, the avatar dies and the user should exit the simulator or remain as a spectator.
- *Stamina bar:* The stamina bar displays the avatar's endurance on physical challenges such as running, jumping, climbing, etc. While the avatar runs or climbs stairs this bar is gradually depleted. When it reaches 0%, the avatar is unable to run, jump or climb stairs.

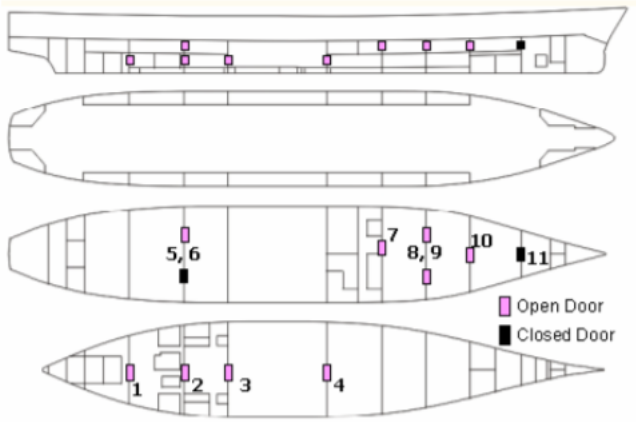
4.2.4 Player controls

An evacuee moves using the mouse and the keyboard keys as listed in Table 1 (the keys indicated by an asterisk are not yet in use).

4.3 Evacuation area

SES is considered a simulator for ships of the passenger ship category, although if the parameters are modified could be potentially used for other categories such as cargo carriers, container ships, fishing boats or recreation vessels (Blix et al., 2015). SES uses, (as its evacuation area) a model of the ro-ro passenger ship EXPRESS SAMINA (Figure 4) modified, based on the official dimensions provided by IMO. The ship has a gross tonnage of 4,555 tons, a length of 115 m and breadth of 18 m and these features have been implemented to the simulation. EXPRESS SAMINA (EXPRESS SAMINA Ship from Vessels Database [online] https://www.marinetraffic.com/ais/details/ships/imo:6613548) has two decks; the lower and the upper deck. The compartments of the lower deck are three cabin areas with multiple cabins connected by two parallel corridors and the lower deck lobby.

Figure 4 Views and decks of the passenger Ro-Ro ferry EXPRESS SAMINA (see online version for colours)



Source: Papanikolaou et al. (2004)

The upper deck's main compartments are the two large sitting areas, the upper deck lobby and the restaurant. Six stairwells allow the passenger to commune between the two decks. The four doors leading to external parts of the ship (balconies) are located at the upper deck and thus are considered as the exit points. The above-mentioned compartments and dimensions have been implemented to the simulator, aiming to improve the realism of the simulations. After reaching any of those exit points, an evacuee is safe. Two exit points are located at the stern, while the other two at the bow of the ship. In this regard, the pathways are based on the pathways of the real ship and the assessment of the result is considered based on this assumption.

The ship's interior is equipped with a number of objects and items that suit the interior of a passenger ship and are listed in Table 6.

Table 6 Ship equipment used in SES

Equipment	*Description*
Build-in beds	Located exclusively inside the cabins, beds are immobile objects, bound to the structure, restricting the movement in the interior of the cabins though the evacuees can step on them, if they jump.
Tables	Located especially in the restaurant area, tables are also immobile and bound to the structure, restricting the movement and can be climbed after a successful high jump.
Chairs	Located in various, are movable items, either by evacuees or by any listing or movement of the ship. Chairs can be a nearly impassable obstacle if block a narrow corridor or an exit.
Speakers	Locate at both decks the speakers broadcast alarms, alerts and messages.
Lights	Spots lights are the main illumination sources for the interior of the ship. Altering their intensity and colour, and administration can switch from full illumination to partial illumination, no illumination or alarm illumination.
Doors	Unlocked doors may automatically open if approached by an evacuee. Locked or stuck ones won't open without the intervention of a crew member.

4.4 AI behaviour and movement

One of the most important features of SES is the simultaneous presence of AI-controlled Bots and human users. The AI system controls the behaviour and the actions of bots, aspiring to simulate regular human evacuees. This feature allows researchers and users to research the behaviour and movement of crowds composed by real players and bots. They can also assess how realistically AI-controlled bots may behave and how effectively can interact with other bots and/or real human users.

The AI system, was developed using the UE4 build-in AI system. More specifically, it was based on the development of behaviour trees (holding courses of actions), blackboards (storing important locations or persons) and special purposed programs called services, decorators and tasks. Behaviour trees were used for developing a tree-like structure of possible actions, that a bot can choose. Blackboards were used for attaching to a behaviour tree (or multiple behaviour trees) and store places, locations and persons, known to the bots. Finally, services, decorators and tasks programs were attached to behaviour trees updating and enhancing them with any newly collected information. The bots can collect information using their senses (hearing and sight) and process this information so that they act accordingly. As an example, if a bot sees a blocked door, the route that passed through that door would not be selected and instead it will start searching for alternative free/open routes. The features of the SES bot's AI decision making system are described below:

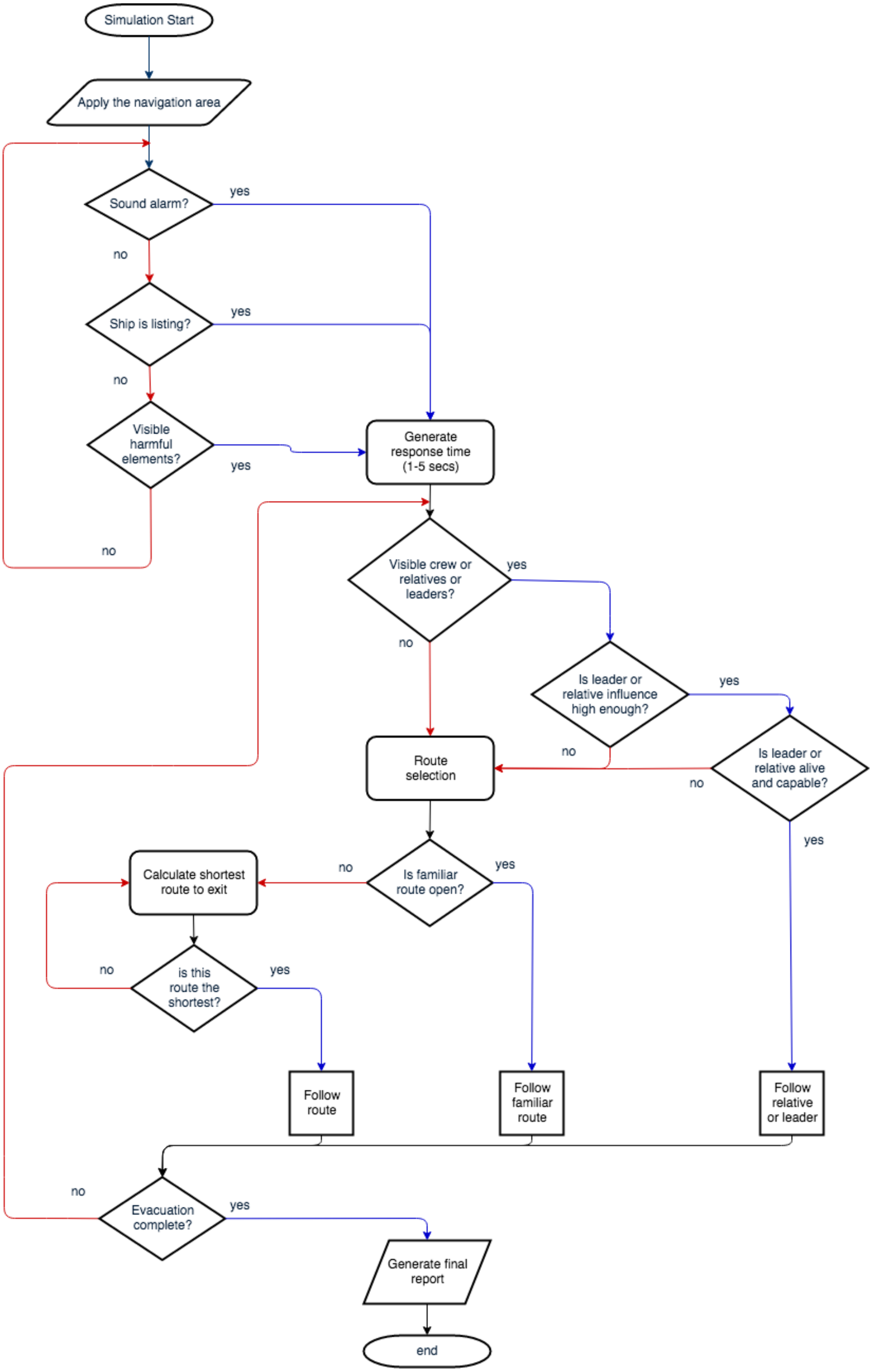
- *Hearing:* The bots can hear sounds, broadcasted from a source located close by and only if the intensity is high enough. This feature is experimental and will be fully implemented to future releases.
- *Sight:* Bots can see with a field of view of 180° degrees centred right in from of their nose. This angle imitates the eyesight and field of view of most adult population.

- *Initial response time:* When a harmful event, such as a fire, first breaks in, the bots initiate a random initial response time. This response timeframe (RT) varies from 1 to 5 seconds, based on the particularity of every evacuee (Zhao et al., 2009). Bots cannot take any action before the expiration of the RT. The initial response time aspires to simulate the time a human being needs to realise, to evaluate and to eventually react after the outbreak of a disaster.
- *Social forces effect:* Studies argue that, after the outbreak of a disaster all the bots are searching for crew members, relatives or leaders in their immediate area (Nilsson et al., 2009). Those followers imitate the actions of the 'leaders', although they may abandon them, if the leaders prove themselves unreliable, leading them to conjected areas or blocked doors.
- *Route selection:* The passengers evacuate using escape paths based on SOLAS Regulation II-2/13, adjusted to match the needs of the simulator, the words in the symbols are printed in English and Greek (EXPRESS SAMINA service area used to be the Aegean Sea in Greece and most of the passenger were of Greek origin). Therefore, the escape paths are designated and labelled, thought, recent studies have shown that the passengers tend to ignore signs and select the shortest or more familiar path. The routes, are continuously calculated, updated and compared with previous ones. In case, a bot is jammed into a crowded location, while it is following a selected route moving toward an exit or an area, after five seconds of very low speed or immobility its starts searching for alternative unblocked routes around it (rerouting). For the selection of their route (initial or rerouted), the bots follow a sequence of steps, as listed below and in Figure 5 in more detail:
  - a Follow-up (F): The first action taken by the evacuees is to follow a leader. Leaders may be crew members or parents, causing the adult bots to mainly follow the first, while kids tend to follow the latter.
  - b Route familiarity (RF): How familiar is an evacuee with an escape route. Studies have shown that the evacuees prefer to use as an escape route, the one they had previously followed to arrive at their current location.
  - c Blocked or not (B): Evacuees usually choose the closest clear (unblocked or unlocked) exit, following the shortest clear path. An obviously closed/locked door or a route blocked by a piece of furniture, fire, smoke, etc., is ignored, unless it is the sole available route.
  - d Estimated selected route (ESR): The ESR is the chosen escape route. Bots calculate the distance and choose the nearest, clear, passable exit path. The ESR is calculated comparing the coordinates of the bot (L_B) and all the observable (by the bots), clear exit spots (L_E). The calculated distances are then compared and the shortest one is chosen. The functions are listed below:

$$D^{1,2,n} = L_B^{1,2,n} - L_E^{1,2,n}$$

$$ESR = M\left(D^1, D^2, D^{n\cdots}\right)$$

Figure 5 The decision-making system of the AI-controlled bots (see online version for colours)



5 Simulator's validation

The architecture described in previous sections and used to implement the simulator SES, is the basis for allowing a lightweight simulation environment, created with a game-engine where designers and operators are able to train their monitoring, planning and re-planning skills without the need of a powerful machine or specific software installation.

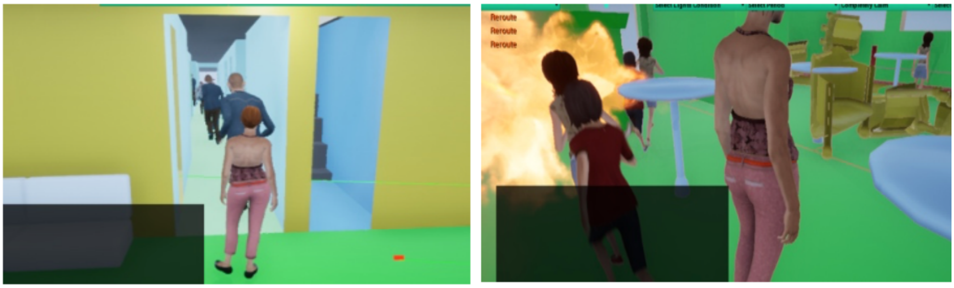
To ensure the proper functionality and scalability of the planned architecture, it was necessary to carry out some tests. To test SES, some basic experiments have been made in order to show that the simulator requirements are low, so any modern computer can run and visualise the simulation correctly. The simulator has been executed using different platforms (desktop and laptops) with several operating systems (Windows, Linux, MacOS.). All of them have performed a constant 30 frames per second (FPS) rate. However, SES cannot be executed in mobile devices and tablets.

A number of simulation-only and single mode scenarios were conducted for the needs of this paper. A PC with a minimum of 16 GB of RAM, can run a scenario, with up to 1,000 bots, without significant performance issues. For more than 1,000 bots, we would propose to use more powerful computers to avoid technical difficulties.

5.1 *Simulation-only mode*

Five evacuation sessions conducted with 600 bots spawned in the interior of the ship. Most bots ($n = 400$) were spawned at the upper floor (restaurant, upstairs lobby and seating areas) and the rest ($n = 200$) were spawned at the lower floor (cabins and downstairs lobby) randomly (Figure 6).

Figure 6 Bots, (a) evacuees attempt to escape the lower deck (b) fire evasion close-up screenshot (see online version for colours)



(a) (b)

The conditions and the results varied depending on the spawned elements (fire, smoke, poisonous gases) and the duration of the session. Each session lasted for 10, 15, 20, 30 minutes, respectively and the last one was terminated when all evacuees had safely evacuated the ship or had been perished.

The initial response time was triggered normally and the bots-evacuees reacted after a period of time varying from 1 to 5 seconds. Bots-evacuees tried to recognise an observable leader-bot, which has been previously assigned by the administrator. The recognition was difficult due to the density of the crowd, the intensity of noise and large size of the ship that limited the ability of the bots to see or hear someone. Only 14% of the bots eventually followed a leader-bot. Moreover, bots walked or run following the shortest estimated passable route, after failing to follow a leader. If the shortest route was blocked a 78%–95% switched to the next shortest route. However, a 5%–22% insisted on following the blocked route.

Some evacuees encountered exit or warning signs and most of them, followed the instructions. Sometimes following those signs, led these bots to select closed or blocked routes. The recognition of exit signs was, also, difficult due to the density of the crowds. A useful conclusion is that if all the evacuees are directed or they decide to follow a specific route, this route could be blocked by the crowds of the evacuees.

Congestion areas appeared near or in front of doors and near or on stairs, as expected. Counter flow was created by some bots-evacuees and affected the speed of the crowds, blocking entrances and disrupting the movement of other evacuees. When the counterflow effect was suppressed by the administrator (even though some bots were moving at the opposite route following their route), the evacuation speed was increased by up to 22%. The ratio of the bots-evacuees that survived varied from 30% to 95% depending on the scenario. The injured, the older and the younger bots-evacuees had lower survival ratio due to their decreased speed.

When the administrator increased the number of the real-time (or initially) spawned harmful elements, the survival ratio of the evacuees dropped. The longest evacuation sessions resulted in minimised casualties (under the same conditions). The 10 and 15-minutes evacuation times made survival ratio drop dramatically. After the expiration of the evacuation time, all the non-escapees are treated as deceased.

5.2 Single mode

Five evacuation sessions conducted with 600 bots and the administrator (Figure 7). No events were triggered, while the administrator was participating as a player. Again, most bots (n = 400) were spawned at the upper floor (restaurant, upstairs lobby and seating areas) and n = 200 were spawned at the lower floor (cabins and downstairs lobby) randomly. All the events and the elements were triggered or spawned before the scenario starts.

Figure 7 Bot, (a) evacuees attempt to escape toward an upper deck exit (b) evacuees attempt to evade a source of fire (see online version for colours)

(a) (b)

The overall results are listed below:

- The bot's survival ratio is increased, if no events and elements are triggered or spawned in real-time.
- The human-bot interaction was observed as expected, as multiple bots used to follow human user's avatars.
- Human users familiar with first-person shooter games have an increased survival rate up to 60%.
- Human users familiar with the interior of the ship have increased survival ratio up to 30%.
- Regarding the initial reaction time, the behaviour of the human users was similar to the AI-controlled bots. After the breaking of an event, most users evaluated the situation for a timeframe from 1 to 5 seconds before taking any other action.

6 Discussion, limitations and future work

After thoroughly testing the simulator, we concluded that the application is capable of representing the conditions and the motion of a passenger ship, while can truthfully simulate the physical qualities, the actions and the movement of human-like evacuees. SES collects the simulated data and the evacuation scenarios can be monitored providing spatial information. The collected data can be stored and analysed later. While it is really challenging to find a large number of testers, SES gives the ability to properly simulate an evacuation scenario with only a small number of users-testers along with several bots while the conditions and the motion of the crowd remains accurate. Towards this direction, future research could assess the optimum human users/bots' analogy, toward the maximum simulation reliability.

Moreover, during all the evacuation scenarios we conducted, the majority of the bots behaved, as expected, waiting until the initial response time expires, detecting all the hazardous elements in their field of view or hearing range, finding exits and following the closest clear paths toward them. Therefore, we conclude that the AI-controlled bots used in SES are capable of imitating the movement and behaviour of a human evacuees, in a high degree and in most of the cases.

Runtime 'unexpected' events, have significantly affected the outcome and output of all the evacuation scenarios. Runtime events are resulted to increased casualty's ratios, an increased overall evacuation time and a higher probability of trapped or isolated evacuees. Furthermore, SES incorporates gamification qualities which seem to immerse successfully the human-users into the simulated environment, pursuing clear, reachable and understandable goals, interacting with human-like bots-evacuees and developing a competitive environment among the participants.

Future works intend to use the proposed simulator as a testbed for HRI researches. Furthermore, with SES we plan to implement: a new crew-member/rescue-team member mode and automatic spreading ability of elements such as smoke, fire and gas and water inlet features. The implementation of sea sickness is also considered as an addition to the bots and human players, in future releases. Some spatial elements (congestions, bottlenecks, etc.) and exclusive computer-based recognition and indication, are also to be included. Later releases of the SES are planned to include machine learning for the bots, in order to learn from their experience and act accordingly. Another major addition will be the implementation on multiple ship categories. Although SES is considered a robust simulator comparing previous works in the field (Ginnis et al., 2015; Stefanidis et al., 2019), the credibility of the results presented here are going to be furtherly enhanced with the implementation of the above-mentioned features and the conduction of simulations, which involve large numbers of human players and bots. Next steps may also examine methods used in various defence organisations where human reaction and performance is a critical mission and have the gaming avatars fitted with blood pressure and heart monitor equipment to measure their true human response to fear, even though within a game, whilst testing the realistic parameters of the simulation. Finally, those results could be compared with data from real evacuation incidents and improve the validity of the results.

7 Conclusions

This paper presents the development of a game-engine-based simulator, called SES, for ship evacuation with realistic conditions. SES is a 3D simulator facilitating the impersonation of evacuees by computer-controlled autonomous bots that perform risk assessment and continuously calculate route conditions, communicate with neighbouring occupants, determine bottleneck points, and select the best evacuation routes.

The proposed simulator collects data of the evacuation scenarios and enables users to observe and evaluate the course of a scenario giving the ability to mix up human users and computer-controlled bots. It also allows us to assess the impact on the reliability of the results of the evacuation scenarios, if AI-controlled bots can act as human beings should have acted and in what degree and how runtime events (fire, fog, etc.) could alter the course of an evacuation scenario.

Ships have become larger in scale and function, and occasionally their complexity has increased considerably. This brings up many difficulties in evacuation and rescue when an emergency occurs. Therefore, effective evacuation and risk methods should be predicted and applied to design, safety training, and education. SES is a lightweight simulator with simultaneous participation of human users and computer-controlled bots as evacuees in gamified multiplayer scenarios by the runtime spawning of 3D elements such as fire and smoke. Realistic and valid results can be obtained by applying SES in evacuation simulation and it has several benefits such as flexible technology and economic feasibility.

The proposed simulator does not aim at this stage at commercial reality, especially since simulators may have significant lifesaving potential. Simulating systems in the marine industry are unable to afford the best treatment for all passengers in all situations. Choices have to be made. This work attempts to immerse users in a game-based environment, and make them feel like they are in a more factual situation and therefore act more realistic. According to this principle SES can help to find ways to save lives, compared with drills or other simulations.

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