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An Agent-Based Ship Firefighting Model

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Abstract: Maritime safety is an ongoing process in shipping that is constantly being improved by the modernization of equipment and constant improvements in operators' safety procedures and training. However, human error remains a significant factor in maritime accidents, as it contributes to 75% of incidents. Addressing this problem, the current paper shows a proof of principal for on-board fire monitoring and extinguishing software agents that may be used to upgrade present systems and contribute to an autonomous ship design. Agent technology that engages fire detection and firefighting equipment while minimizing human intervention will reduce the risks of human error and increase maritime safety.

Keywords: autonomous decision making; intelligent agents; multiagent systems; ship fires

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1. Introduction

A fire on a ship is one of the most dangerous incidents which can happen on board. For some time now, the use of agents has proved to be a useful solution in many technical areas, and it is justifiable to explore the suitability of the use of agents in ship's firefighting systems. The agent is a physical or virtual system that perceives its environment by various sensors and acts on it through its actuators. Agents work in their environment and can include people, robots, or computer programs.

Research on the use of agents in ship fire protection processes is justified for several reasons. The first reason is to remove people from the processes related to fire detection and extinguishing. The role of people in the processes related to fire detection and extinguishing can be taken over by agents. This is important for two reasons. The first is that, in this way, we reduce the possibility of bringing people into potentially devastating situations that can occur during fire extinguishing. The second reason for the use of agents in ship fire protection processes is related to the quality of decision making during the incident caused by the fire. Human decision-making during critical situations can be problematic for many reasons such as fatigue, fear, or a lack of training to handle such situations. The application of agents reduces the possibility of poor decisions due to human error.

In this paper, we present our ship firefighting model based on agents. The proposed model can be used as a supporting system on board conventional ships as well implemented on autonomous ships. When using the model on regular ships, it is necessary to introduce mechanisms for detecting the presence of human persons in rooms where fire is detected. This can be achieved in several ways, for example by using infrared cameras or appropriate smart RFID bracelets that crew members would be obliged to wear continuously. Agent knowledge and decision-making methods can then be adjusted depending on whether human beings are detected in fire areas.

The reason for the use of agent systems in the establishment of ship firefighting systems is the interoperability of the system of autonomous vessels. An autonomous vessel can be designed as a set of interconnected systems where each system assumes responsibility for the operation of a particular segment of the vessel. Harmonious operation of an autonomous vessel is difficult to achieve without interoperability of these systems. Agent systems, using appropriate ontologies and common communication frameworks, can represent a high-quality solution to interoperability requirements.

This paper is conceptually divided into two parts. The first part discusses theoretical foundations related to a ship's fire protection, multi-agent systems, agent-based modeling, and simulation. The author's model of the agent-based ship firefighting model, as well as an overview of the implementation of this model, is given in the second part.

2. Ship Fire Protection

The ship's voyage is maritime venture from the beginning of loading cargo at the departure port to cargo unloading in the arrival port. On her voyage, a ship is exposed, not only to hostile marine environments, but to various internal hazards. Since the tragedy of the RMS Titanic in 1912, the prevention of hazards on sea voyages is constantly improving via various safety rules which originate from the International Convention for the Safety of Life at Sea, 1974, as amended—SOLAS [1]. Classification societies, such as Croatian Register of Shipping, have provided Rules for the Classification of Ships, which includes a Fire Protection section [2].

Fire or explosion is the leading cause of harm to people and property on board ships, resulting in major distress and a loss of cargo, ships, and human life.

In order to reduce risk, technological advances, as well as expert knowledge, are included in fire detection and fire extinction on board ships regarding SOLAS, Chapter II-2, revised on 1 July 2002. Foremost, fires should be prevented from occurring. Secondly, materials used for ship construction should be non-combustible materials. Thirdly, any fire should be contained and extinguished [3].

In order to design and maintain ship fire protection, firefighting equipment has to be installed on board ships from an early stage, during its building process in shipyards. Plans for fire detection and extinguishing systems must be included to prepare her for fighting any kind of fire. However, the ship is not only a technical system; it also includes on-board persons who vary in their duties, education, and training levels. Human error is often investigated as a risk factor [4]. Ship fires or explosions are one of the leading causes of ship loss, cargo loss, or human injury. The presence of such risk factors has led to the development of technical standards, such as the International Code for Fire Safety Systems—the FSS Code [3]. Crew education and training are ensured through the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers—STCW [5], which declares minimum levels for maritime education, training practices, and competence. In accordance with [6], human error contributed to 75% of fires and explosions. Several studies have investigated various solutions to reduce Human Error Probability (HEP), e.g., [7].

The fire on board a ship is a selected distress situation in which the human factor will be substituted using agent technologies. Both fire detection and fire extinguishing systems of a real ship will be simulated [8].

The ship fire detection is designed in accordance with the Convention, Chapter II-2. Detectors used on board ships for fire detection include flame detectors, heat detectors, and smoke detectors. Flame detectors monitor the light produced by a flame that has a characteristic flicker frequency of about 25 Hz and subsequently trigger an alarm. Heat detectors are usually designed by means of a bi-metallic type with thick and thin strips detecting elements. The thin strip is more sensitive to increases in temperature than the thicker one. A sudden rise of temperature and/or temperatures exceeding 75 °C will cause the strips to bend and come into contact, thus triggering the alarm. Flame detectors operate using light obscuration or ionization.

In addition to the fire detection system, for efficient ship fire protection, a fixed fire extinguishing system must be properly designed and installed in protected spaces. Various extinguishing systems depend on the location and type of fire. The most common firefighting systems on board ships are fire mains and hydrants driven by fire pump(s) with sufficient flow capacity and pressure to reach the highest and farthest areas of both ship and cargo. Other systems used on board ships are mobile or fixed gas (e.g., CO_2), fire powder, or foam systems. Systems used for fire extinguishing vary across spaces (accommodation, cargo holds, or machinery spaces) and flammable materials (e.g., fuel, oil, electricity, or solids).

Fire propagation characteristics for a desired ship space should be analyzed, in order to design the mathematical and physical models of ship fire simulation. Parameters have to be set, such as the simulation calculation area, the setting of fire source information parameters, boundary conditions, and working condition [9]. Ship fire hazards have been taken into account [10], where the rapid development of fires in the closed cargo compartments of ships has been analyzed. Fire fuel characteristics for modeling fire, such as the Heat Release Rate (HRR), are currently taken into account to design the relevant mathematical models.

Since the initial development and practical implementation of Maritime Autonomous Surface Ships (MASS), ship fire protection has been one of the central safety issues and requires continuous improvement, which contributes to the Standard Training for Watchkeeping (STCW) for successful operations [11]. Some researchers even explored the role of computer leadership [12]. The International Maritime Organization's (IMO) Maritime Safety Committee (MSC) finalizes an analysis of ship safety treaties seeking to identify the issues required for regulating MASS with special interest given to fire safety systems and operations regarding firefighting. Ongoing challenges for firefighting safety are escalating (e.g., for the passenger ferry). Extinguishing a local fire manually (e.g., a battery in an electrically powered vehicle) can lead to additional fatigue for an already overloaded crew and may result in poorer performance of other emergency tasks, such as evacuating passengers. The complexity of fire problems can escalate if the on-board cargo includes lithium ion batteries. Therefore, fire prevention strategies must be designed accordingly [13].

Thus, novel approaches to ship fire protection problems are needed and should include simulations of a ship in all fire-protected spaces during ship design and in validating existing systems.

3. Multi-Agent Systems and Agent-Based Modeling and Simulation

The ship firefighting model presented in this paper is based on multi-agent systems (MAS). Our model has been simulated and evaluated using an agent-based simulation tool, i.e., NetLogo.

MAS have been investigated in computer science for approximately three decades. Whilst several definitions of agents have been proposed, that proposed by Wooldridge [14] is most commonly used and defines an agent as a computer system that is situated in a certain environment and that is capable of autonomous action in this environment in order to meet its design objectives. An agent is intelligent if, besides autonomy, it possesses the properties of reactivity, pro-activity, and social ability. Following this definition, a MAS is defined as a system consisting of numerous agents, which interact with one another. MAS has been defined in [15] as a system that includes the following elements: an environment E, a set of objects O, an assembly of agents A, an assembly of relations R, and an assembly of operations Op, making it possible for the agents of A to perceive, produce, consume, transform, and manipulate objects from O, and for operators to specify tasks and reactions of the world.

MAS and agent-based modeling (ABM) are closely related [16]. Indeed these terms are not easily differentiated and are often used synonymously in many papers [17]. The benefits of ABM over other modeling techniques include ones in which (i) ABM captures emergent phenomena, (ii) ABM provides a natural description of a system, and (iii) ABM is flexible [18].

Often, when a live experiment cannot be performed because the real system is dangerous, not accessible, or too complex, a simulation is used. Moreover, simulations enable a better understanding of the system as well as an identification of possible improvements.

Furthermore, a computer simulation provides a safe and affordable way of including all scenarios of the problem like the case presented in the current paper (i.e., a fire on board).

Agent-based modeling and simulation (ABMS) refers to a category of computational models invoking the dynamic actions, reactions, and intercommunication protocols among agents in a shared environment [19]. It enables an evaluation of the design and performance of agents and the comprehension of their emerging behavior and properties.

ABMS tools simulate realistic scenarios with groups of agents interacting with each other. Agents can be simple entities with no cognitive representation (i.e., reactive agents), intelligent objects with rich cognitive representation (i.e., Belief, Desire, and Intention—BDI), or a combination of different cognitively capable agents. The basic idea is to model complex systems adopting a bottom-up approach, starting from individual agents [20].

Similar to MAS, there is no consensus on the definition for ABMS. However, the reference [17] provides four alternative definitions with increasing complexity: (i) an individual ABMS, (ii) an autonomous ABMS, (iii) an interactive ABMS, and (iv) an adaptive ABMS.

ABMS is recognized and applied in many scientific disciplines, not only in Science, Technology, Engineering, and Mathematics (STEM) but also in the natural and social sciences [21]. With regard to STEM, ABMS has been applied to several disciplines, such as the design of self-organizing systems [22], geographic information systems [23], epidemiology [24,25], ecology [26–28], transportation and logistics [29–31], manufacturing [32,33], design of critical systems [34–37], and cloud computing [38]. ABMS is also well suited to the social sciences, where an understanding of the individuals and how they interact is important for understanding the synergy effect and emerging behavior of systems. Thus, ABMS is implemented in business [39], finance [40], management [41], tourism [42,43], politics [44], urban planning [37], psychology [45,46], and education [47]. To date, numerous ABMS software tools have been developed, and comprehensive surveys of these tools have been presented [19,48–52]. The choice of an ABMS tool in the current study is based an evaluation of 85 agent-based toolkits [19], which were further refined according to the current research requirements (see below) so that the NetLogo platform could be selected. NetLogo [53] is a multi-agent programmable modeling environment for simulating natural, technical, and social systems [47,54,55], and it is widely used for agent-supported modeling and simulation [51].

4. Ship Firefighting Model Based on Agents

Autonomous vessels cannot be achieved without establishing interoperability of many automated ship systems. Therefore, each system installed on an autonomous vessel should be clearly defined in order to achieve interoperability with other installed systems. The precondition for achieving interoperability is to enable the exchange of information between built-in systems. This can be done by defining the ontology of those areas that the built-in systems cover. Ontology is an explicit specification of the concept of an area [56,57]. The ontology of a given area contains the categories of that area, the relations between categories, and the properties of defined categories. The agreement on the use of ontology in an area enables the sharing of "ways of understanding" in that area. The use of the same ontology in an area prevents the possibility of misunderstanding in communication. These misunderstandings occur when using different terms for the same elements of the area, the same terms for different elements of the area, different models of connecting elements of the area, or different rules on concluding over elements of the area.

The ontology related to our ship's firefighting model contains the following elements:

(i) Ship elements that are relevant to fire detection and fire extinguishing, such as infrared cameras, smoke detectors, and foam generators. In the formal definition of ontology, these elements will be called categories and marked denoted using the letter K.

(ii) Relationships between ship elements relevant for fire detection and fire extinguishing. In the formal definition of ontology, these elements will be called relations and denoted using the letter R.

(iii) Properties of ship elements relevant for fire detection and fire extinguishing. In the formal definition of ontology, these elements will be called the categories' properties and denoted using the letter P.

Formally, we define the ontology of our model as an ordered triple (K, R, P) where
$K = \{K_1, K_2, \ldots K_n\}$ is a set of categories of an area,
$R = \{R_1, R_2, \ldots R_m | \ R_i \subset K^n, n \geq 2\}$ is a set of relationships on K, and
$P = \{f: \ DP \rightarrow \ AV \mid DP \subset K, \ AV \subset K \cup BDT\}$ is a category property set, where f is a category property name, DP is a category property domain, AV is a category property value area, and BDT is a set of basic data types.

This definition enables the category property to be a category but also a basic data type. The ontology created according to this definition can be represented using semantic networks. Figure 1 shows a part of the categories of the model presented here. The semantic network of these categories is presented. Rounded rectangles show categories (K), while relations (R) between them are shown with arrows.

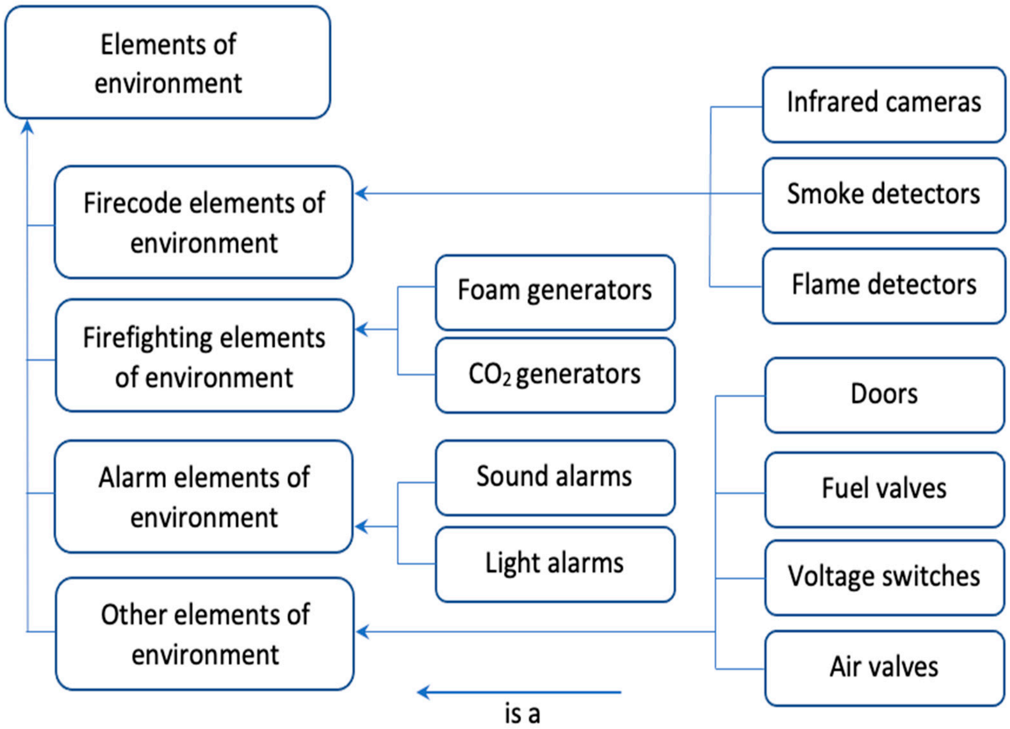

Figure 1. Part of the semantic network of model categories.

The categories are associated with properties. Table 1 shows part of the categories and their associated properties. In the same way, appropriate properties are associated with other categories of models. In the proposed model, each ship room is joined by an agent in charge of the fire protection of that room. The elements of the environment in the room are agent sensors and actuators. By scanning the properties of its sensors, the agent receives information about the state of the environment.

Table 1. Part of the categories (K) and their associated properties (P).

Kategory Name	Property Name	Allowed Property Values
Ship rooms	ID	Room identification number
	Permitted_method_of_ extinguishing	"CO_2", "foam", "CO_2 and foam"
	co2_quantity	Required number of CO_2 units (sufficient to extinguish the room)
	foam_quantity	Required number of foam units (sufficient to extinguish the room)
Infrared cameras	ID	Infrared camera identification number
	location	The coordinates on which the infrared camera is located
	fire_detection_status	"fire in space", "no fires in space", "raised level of vigilance"
	persons_in_room	number of persons in the room
Foam generators	ID	Foam generator identification number
	Activity	"in the process of generation", "inactive"

For example, the agent receives information about the existence or non-existence of fire in the room by reading the value of the fire_detection_status property of the infrared camera. Likewise, the agent can change the state of its environment by changing the properties of its actuators. For example, the agent activates the assigned foam generator by changing the value of the activity property from "inactive" to "in the process of generation." The agent's knowledge is represented by production rules, such as the following production rule [58]:

if smoke_detector.detection_state = "smoke in the room" then
{if (ir_camera.fire_detection_state = "fire in space" or
ir_camera.fire_detection_state = "raised level of caution")
then {
sound_alarm.activity = "active"
light_alarm.activity = "active"
... }

This model can be configured according to any real ship environment. The design of the real ship determines which fire elements will be implemented in different vessel spaces. Ship spaces are designed together with fire extinguishing equipment used to protect such spaces. The type of fire extinguishing systems is designed and calculated regarding the purpose of the spaces in order to protect those spaces. Agent technology will activate those systems when needed. An example of one configuration is described below.

5. Implementation of the Model in an Agent Simulation Environment

The evaluation of the agent ship-firefighting model was done in a programmable environment for the simulation of agent and multiagent systems. The simulation system was built to support real parameters related to fires on board. This required the selection of an appropriate platform that supports the agent/multiagent simulation environments, with the following mandatory conditions:

(i) the platform must enable the use of a programming language for both the environment and agents;

(ii) the platform must enable the implementation of sufficiently complex models in order to implement the proposed model;
(iii) the platform must enable the extraction of internal data of the states of agents during the performance of their tasks—this condition is mandatory due to the subsequent analysis of the data to be obtained by the simulation.

In addition, the following desirable (but not mandatory) conditions have been set:

(i) the platform must enable as rapid development as possible without affecting the quality of the built system;
(ii) the platform must be well documented;
(iii) the platform must be demonstrated to be used in independent research and outside the institution where it is developed;
(iv) the platform must be adapted to current versions of operating systems (the last version of the platform must not be older than two years).

Considering mandatory and desirable conditions previously mentioned and a survey given by [19], the NetLogo platform was selected as optimal.

A simulation environment based on the described agent ship firefighting model has been developed. This simulation environment robustly simulates the space–time relationships between the spreading and extinguishing of fire. This was achieved during the definition of simulation parameters when the realities of space–time relations between all relevant processes were checked. In this way, relations between the speed of the spreading of fire, the distribution of CO_2 in space, the speed of spreading foam, and other parameters were verified. The time of execution of the process within the simulation is calculated in the time units of the simulation. These units are invariant to the processor speed. With respect to other time relations, realistic times of fire propagation and extinguishing are achieved. The supervision of fire protection elements is left to agents who behave exactly according to the defined agent ship firefighting model. Therefore, with this simulation environment, it is possible to show the following:

(i) a ground plan of any real ship environment;
(ii) various firefighting elements and their states and positioning within the ship' environment;
(iii) simulation of one or more simultaneous fires occurring in any part of the ship's environment;
(iv) simulation of fire detection and extinguishing using a developed agent ship firefighting model.

The developed system records every moment of fire and all actions taken by the agent. These data are later used to evaluate the performance of the developed model. Figure 2 shows the user interface of the developed system.

The user within the user interface can set initial fire conditions. Parameters such as the number of concurrent fires, the initial fire locations, the presence of people in burned rooms, the condition of the openness of the valves, and the switches in fire spaces belong here. Figure 3 shows a simulation of simultaneous fire in all the ship rooms presented.

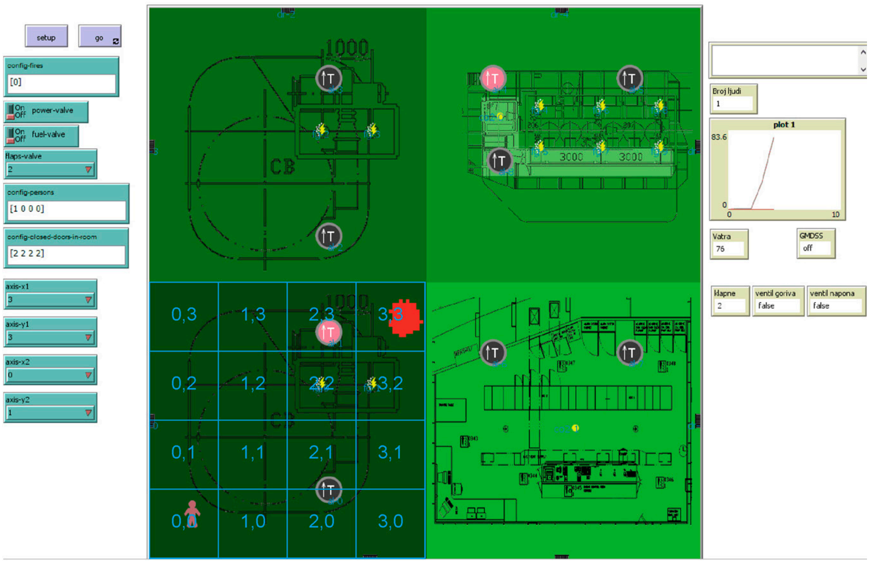

Figure 2. User interface of the developed system.

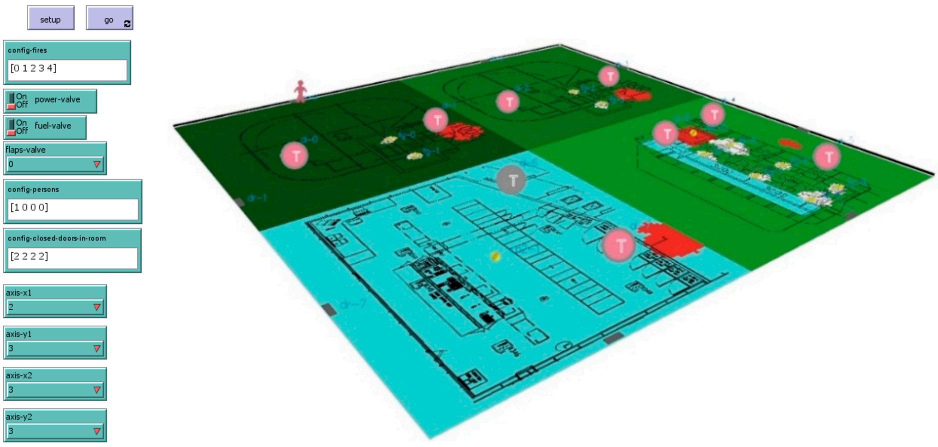

Figure 3. Simulation of simultaneous fire in all rooms.

The developed system enables the random generation of initial fire parameters. In order to be able to calculate the efficiency of the proposed model, the system enables the calculation of the results of extinguishing all possible variations of initial fire parameters. The number of possible variations of initial fire parameters depends on the complexity of the set configuration of the environment. Table 2 shows part of the configuration of the environment used in simulating fires for the purpose of this paper. For a complete definition of configuration, it is necessary to define the ground plan of the rooms as well as the exact position of the elements of the environment. Figure 4 shows the ground plan of the control room of the engine room. The ground plan of the rooms as well as the positions of the elements of the environment should be defined for a realistic simulation of both detection and fire extinguishing. Each defined configuration of the environment can be exported to any format that supports semantic data description.

Table 2. Part of the configuration of environment.

Room Type	Number of Rooms in Configuration	Elements of Environment Located in the Room *	Mode of Extinguishing
Fired boiler room	2	Infrared camera (1) Smoke detector (1) Flame detector (1) Foam generator (2) Door (2) Fuel valve (1) Air valve (1) Voltage switch (1)	Foam
Main engine room	1	Infrared camera (1) Smoke detector (1) Flame detector (1) Foam generator (6) Door (2) Fuel valve (1) Air valve (1) Voltage switch (1)	Foam
Engine control room	1	Infrared camera (1) Smoke detector (2) CO_2 generator (1) Door (2) Fuel valve (1) Air valve (1) Voltage switch (1)	CO_2
Main engine scavenge air space	1	Infrared camera (1) CO_2 generator (1) Fuel valve (1)	CO_2

*—numbers in brackets indicate how many individual elements of the environment are located in a particular room.

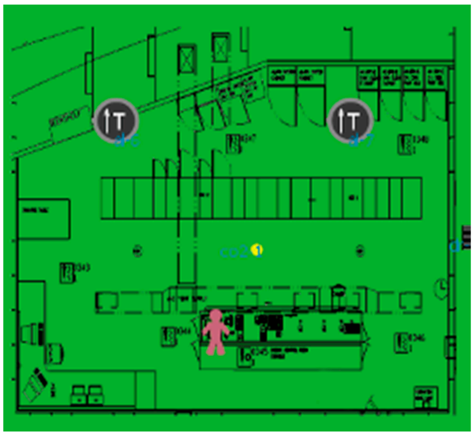

Figure 4. The ground plan of the control room of the engine room.

When simulating all fire variations following the configuration shown in Table 2, the system found a total of 650,880 different fire possibilities. Calculation of the outcome of the extinguishing of all these fires was performed. In a log database, every change of states was recorded for every fire. Figure 5 shows the graph of time needed to extinguish each of these fires. Therefore, it is evident that the proposed agent ship firefighting model extinguished all simulated fires between 21 and 384 s from the moment the fire occurred. The graph shows two local maximum levels in the 69th and 75th seconds of fire, respectively. These two moments are related to extinguishing fires with CO_2 gas. The reason for such grouping of values is the independence of CO_2 propagation from other parameters within the room. Due to the predictability of the speed of expansion and the time needed to extinguish with this gas, these simulation times measured in this way represent the real values of hypothetical events in the real environment. Overall, the average time taken to extinguish fires is 225 s.

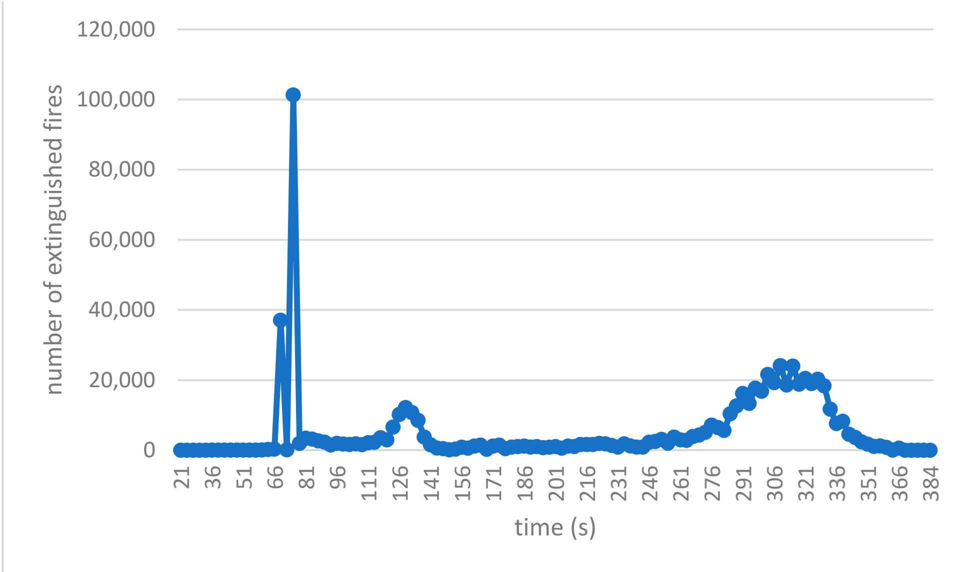

Figure 5. Time required to extinguish all 650,880 simulated fires.

6. Discussion

Safety-raising research is important for both regular and autonomous ships. In this area, there are many possible directions of action in order to raise safety. It is thus possible to proceed with research on, e.g., non-flammable quality materials, improvements in crew training, and the development of better firefighting procedures. Our intention to contribute in this area is to introduce multiagent decision-making systems for actions related to detection and the extinguishing of fires on board. We have developed a ship firefighting model based on agents. Within the developed model, agents are delegated management of all firefighting elements of the ship.

The use of MAS related to fire onboard is not yet sufficiently represented in the literature. We found three papers on this topic [59–61].

In [59], an agent-based modeling is applied to develop workflow simulations involving a ship's crew conducting routine maintenance, watch duty, and reporting functions. A fire was used as a representative emergency scenario, but the authors emphasize that a fire simulation is extremely resource-intensive in terms of computational time and, thus, impractical for their application. Therefore, a simplified fire model was used.

In [60], a MAS approach for shipboard firefighting simulation is presented. They described the architecture and cooperation mechanism between agents, but simulation and simulation results are not presented.

A multi-agent metareasoning approach that enables a multi-agent team to select which task allocation algorithm to use as a function of changing communication quality level is presented in [61]. Their metareasoning policy was tested in three types of scenarios one of which is fire monitoring.

The current paper highlights the need to facilitate interoperability of all ship systems in terms of both personnel reduction and autonomous vessels. The use of common ontologies can be one of the foundations for establishing the interoperability of autonomous ship systems. Therefore, the system presented here has the function of communicating with other systems through the exchange of data described by common ontology. All functions of the system are fully managed by agents. This implementation of the system does not determine the architecture of the systems in the environment. It is possible to realize them with different technologies. It only matters that each one uses a common ontology. Further research will include the simulation of reactions to shipping fatalities precisely through the interoperability of such systems.

7. Conclusions

In this paper, we present our model of an agent firefighting system on board. In order to demonstrate the efficiency of our model, we developed an appropriate simulation environment. The presented case where the system recognized the possibility of an outbreak of 650,880 different fires was obtained by simulating the real environment of the ship in real use, as well as by simulating the actual schedule of firefighting elements on that ship. This represents only one possible configuration of the ship firefighting system. The developed simulation environment enables the analysis of any defined configuration of the ship firefighting system. By setting different configurations within the ground plan of real ships, it is possible to define the most appropriate firefighting configuration for a particular ship. The automation of this process will be one of the directions of future work. Searching for an optimal configuration will be achieved by testing all possible configurations of firefighting elements within the given space. Each variant will pass through a test for all possibilities of fire occurrence. Finally, the data generated by the simulation will determine the optimal configurations of firefighting elements.

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