Multi-agent Simulation of Passenger Evacuation from a Damaged Ship under Storm Conditions

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Abstract
We present a multi-agent model for the simulation of evacuation processes considering ship motions and a method for modeling crowd dynamics. To take into account all aspects of the specifics of evacuation in storm conditions, an information model has been developed. This model is based on three interrelated processes: sea waves dynamics, ship motions under the influence of sea, crowd dynamics affected by ship motions. In our research, we developed a combined method for simulating agents’ movements on the inclined decks of the ship. Our approach combines the well-known implementation of the Social Force model with the possibility of collisions with obstacles. Depending on the specific requirements, it is possible to use various models for ship dynamics in irregular seas. To better support this versatility, a distributed test bench based on the CLAVIRE cloud platform was developed for simulation of passenger evacuation and testing simulations were carried out. The obtained results demonstrate that the developed simulation system could be used for designing contingency plans to assist crew members in the framework of decision support systems (DSS).

Keywords: evacuation processes, multi-agent simulation, ship motions, crowd dynamic models

1 Introduction

In the past few decades the popularity of passenger cruise lines has been growing and therefore the problem of possible maritime disasters is becoming increasingly important. According to statistical estimates (Riola & Arboleya, 2006; Tezdogan et al., 2014), each year about 10 million people travel on more than 230 cruise ships worldwide. For designers and operators of sea passenger ships, a key challenge is to ensure a comfortable and safe stay of the passengers and crew onboard. There are three main groups of tasks to be solved in the field of maritime safety:

- How to prevent occurrences of emergency situations?
- How to prevent the development of an emergency?
- How to minimize losses (human ones, in the first place) in case of an uncontrolled development of the emergency situation?

The last group of tasks is typically associated with the problem of fast and safe evacuation from a damaged vessel which represents an important element of safety at sea. Evacuation may be performed in various emergency situations, not necessarily associated with flooding. For example, fire and smoke aboard, or inability of a cruise ship to perform her mission (failure of power plants, grounding) can also require evacuation. Success of the evacuation from the damaged ship depends on many factors, such as the crew proficiency, ship safety performance, individual characteristics of the passengers’ behavior (reaction to emergency) etc. Correct and efficient evacuation management is of primary importance in emergency situations. That is why it is essential to possess a tool for simulating such processes.

The problem of simulating emergency evacuation from a damaged ship has already been studied in a number of publications some of which are cited in Table 1 and where the corresponding mathematical models/simulation systems are briefly commented and compared. All these software systems use multi-agent simulation. Almost all existing systems try to model passenger movements and to estimate influence of ship motions using velocities- or accelerations-based models but not all of them explore the influence of ship dynamics (irregular waves) on the evacuation process. The existing models, at best, account for quasi-steady inclinations of the deck neglecting local accelerations caused by ship motions in waves (mainly heave, pitch and roll) while it is evident that local acceleration of the deck beneath each agent may work as additional aggravating factor. Influence of the deck inclinations is typically accounted for by means of empirical reduction factors. Also, considering the velocity of a human agent as the primary parameter describing his/her movements is not entirely correct as the advance of an individual is also affected by both physical and so-called social external forces.

<table>
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<tr>
<th>Source</th>
<th>IMEX (Kim et al., 2004)</th>
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<th>Evi (Azzi et al., 2011)</th>
<th>Maritime EXODUS (Gwynne et al., 2003)</th>
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Table 1: A comparison of existing solutions
2 Problem Statement and Informational Scheme

Typically, the main considered parameters characterizing the process of evacuation from various objects (not only from ships or other moving platforms but also from landed aircraft, buildings etc.) are (Duives et al., 2013): the evacuation time (or its expectance, variance, probability distribution); the crowd density (capacity); percentage of human losses.

These parameters can be estimated using various mathematical models depending on the evacuated object’s specifics. Crowd dynamics based on macroscopic continuous fluid-like models proved to be adequate for sufficiently vast pedestrian spaces but regarding movements of passengers on such marine craft as passenger ferries or cruise vessels we have to deal with specific geometric constraints imposed by relatively small cabins, narrow corridors, steep stairs etc. and stormy conditions can bring additional complications. Because of this, movements of evacuated passengers and crew members become different from those in more spacy and steady environments and their specifics can only be treated appropriately by more flexible microscopic models. More or less intense ship motions may change the behavior of both passengers and crew, for instance, periods of active advance may become interlaced with persons just attempting to keep their balance temporarily resigning from heading to an exit. Also, the frequency of possible collisions between the passengers and with obstacles increases. For that reason, we use multi-agent modeling in our simulation.

Our mathematical model for passenger evacuation from a damaged ship under storm conditions is in fact multidisciplinary as it is based on three interdependent processes forming some hierarchy: sea waves dynamics; ship motions under the influence of sea waves; crowd dynamics taking into account the ship motions.

The model must satisfy the following requirements:

- The evacuation process should be described by a microscopic multi-agent model taking into account not only physiological but also psychological characteristics of the agents as long as these may affect the individuals’ behavior during the evacuation.
- In order to model crowd dynamics appropriately, it is necessary to account for the influence of instantaneous ship roll and pitch angles and of local accelerations induced by ship motions;
- For realistic reproduction of the external environment’s it is desirable to consider ship motions in waves pitching ship in most general formulation i.e. 6DOF in natural irregular seas and, possibly, subject to wind gusts although reasonable simplifications may be allowed.

As result, in our multi-agent system, the geometric environment is presented as a 2.5D ship model in the sense that considered is a set of decks linked to each other by stairs, elevators, and, possibly, gangplanks. Considered are also graphs for agent path finding generated by the quadtree method for the space rasterization. Inaccessible itineraries may happen due to local unfavorable factors (for example, exits may become blocked by shut watertight doors or by pieces of cargo displaced by intense ship motions). Also, some paths may become inaccessible as result of flooding, fire, or smoke.

In our multi-agent system each agent is represented by an object with unit mass presented by the tuple:

$$A = \{(x, y, k), P, M(\text{POI}_i^{\text{in}}, \text{POI}_j^{\text{out}})\}$$

where $x, y$ are the agent’s coordinates in the ship-fixed frame, $k$ is the deck number substituting the agent’s applicate, $P$ is the vector of individual characteristics of the agent, $M$ is a function (operator) describing formation of the agent’s path between the starting Point Of Interest $\text{POI}_i^{\text{in}}$ and the end point $\text{POI}_j^{\text{out}}$. 
Individual characteristics of an agent are represented by discrete features classified as follows:

- physical capabilities: fitness, age, gender, degree of disability, professional skills;
- psychological state: active passengers (leaders), self-controlled passive passengers, and passengers hit by panic;
- readiness for evacuation: trained crew members, instructed or uninstructed passengers.

The function $M(POI_{in}^i, POI_{out}^j)$ creates the agent’s planned (desired) route basing on the set of points of interest and on the agent’s personal characteristics $P$. The defined planned route may, however, be dynamically modified under influence of changing ambient and situation. The very function $M(POI_{in}^i, POI_{out}^j)$ can also be modified as result of continuous analysis of the situation performed by the agent. The following principles for path laying presumably reflecting behavioristic patterns of real people in evacuation (Yue et al., 2014) are adopted in our model:

- The path is chosen in accordance with the evacuation plan or following other agents.
- Choosing the shortest path to a desired waypoint basing on the agent’s own preferences (active passengers);
- Following the leader or staying in the cabin in absence of the leader (passive passengers);
- Uncontrolled and possibly chaotic movements in case of panic.

![Figure 1: Scheme of information model](image)

The main inputs triggering the agents or their actuators (legs and arms) are:

- Voice messages received via the ship PA network and intercom (for crew members) including the message announcing the start of evacuation, messages about blocked paths and individual tasks for the crew. As result, an initial configuration of the function $M$ is generated and an evacuation itinerary is defined;
- Dynamic assessment of the current situation by each agent (mostly visual) and by the crowd as a whole allowing each agent to adjust the speed and direction of movement to avoid collisions with other agents and obstacles. This input is dominating for passive agents “following the leader” or “staying in the cabin”. In the latter case, the passengers typically start the motion after appearance of active passengers or crew members in view;
- Perception of danger through audial, visual, olfactory and other channels. In particular: flooding, ambient temperature changes, fire, smoke, poor lighting. All this may initiate the route re-planning and alterations although in general reactions can be very different depending on the individual profile of the agent;
Vestibular perception of alternating changes in the deck inclinations and local accelerations which typically results in:

- Speed reduction at moderately significant ascending and descending deck slopes while at larger inclination angles the individual may stop completely only trying to keep his/her position. At the same time, some speed increase is possible in rather gentle descent;
- Attraction to local points of interest, such as the nearest handrail or wall considered as aids for maintaining equilibrium;
- Response (adaptation) to local external accelerations.

Additional actions or events corresponding to the agents temporary or permanent (death or serious injury) incapacitation: (1) an occasional fall of the agent at large deck inclination angles (in case of fall from the height exceeding 2m the mortality rate is assumed to be 10%). Also, the agent may hit some rigid obstacle or bulkhead do to sufficiently large acceleration in the deck plane; (2) an agent being trapped in some dead end, blocked by a shut watertight door or incapacitated as result of activation of the fire extinguishing system. Entering agent in the zone of the outlet which is not possible in the process of evacuation. For example, in isolated compartments, in a partially flooded premises closed watertight bulkheads in a fire-extinguishing system operating without personal protective equipment.

The study is limited to three types of the crowd control: centralized management of the evacuation process through the ship PA network for all passengers; direct guidance by competent crew members which means implementation of the pattern “follow the leader”; submission to social groups (e.g. family) leaders.

Figure 1 represents the integrated information model linking the main entities under the multi-agent approach. It should be emphasized that this model is phenomenological in the sense that it only reproduces certain observed facts of the human behavior directly related to the evacuation processes.

3 Description of Mathematical Model

Full implementation of the scheme described in the previous section, it is necessary to develop a method for simulating movements of the agents, combining the social force formalism with the possibility of taking into account the physical forces acting on the agents due to ship motions in waves. The latter requires some suitable submodel for simulating the ship motions and computing the local displacements, velocities and accelerations. The implemented models and methods must be suitable for various types of numerical experiments and for investigation of evacuation process with various degree of refinement.

3.1 Crowd Dynamics Model

We have developed a combined method for simulating agents’ movements on inclined decks of the ship. Our approach combines the so-called Social Force (SF) model (Helbling & Molnar, 1995) with an additional algorithm handling possible collisions with obstacles. Agents’ movements are described within the framework of a multibody problem in which a change in the kth individual’s velocity $\vec{v}_k$ with the unit mass is described by the equation:

$$\frac{d\vec{v}_k}{dt} = \vec{F}_k(t) + \vec{\varepsilon}$$

(2)

where $\vec{\varepsilon}$ is the random fluctuation associated with the heterogeneity of the population, $m_k$ is the mass of the individual, and $\vec{F}_k$ is the total force consisting of the following components (Balakhontceva et al., 2015):
\[
\vec{F}_k(t) = \vec{F}_k^{(0)}(v_k, \nu_k^a, e_k) + \sum_j \vec{F}_{kj}(e_k, r_k - r_j) + \sum_n \vec{F}_{kn}(e_k, r_k - r_n^k) + \\
+ \sum_l \vec{F}_{kl}(e_k, r_k - l_i, t) + \kappa \left[ \vec{F}_k^{(R)}(\vec{X}, \dot{\vec{X}}, \ddot{\vec{X}}) + \vec{F}_k^{(S)}(\vec{X}, \dot{\vec{X}}, \ddot{\vec{X}}) \right]
\]

In this equation \(\vec{e}_k\) is the unit vector representing direction of the movement of the agent; \(\vec{F}_k^{(0)}\) – the force caused by acceleration of the agent; \(\vec{F}_{kj}\) – the repulsive interaction force between the agent \(k\) and the agent \(j\); \(\vec{F}_{kn}\) – the repulsion force due to interaction between the agent and the obstacle; \(\vec{F}_{kl}\) is the attraction force between an agent and such objects like other passengers, handrails etc. All these forces are interpreted in the spirit of the SF concept. Additionally, the equation (3) is augmented with terms depending on the vectors \(\vec{X}, \dot{\vec{X}}, \ddot{\vec{X}}\) which describe the linear and angular displacements, velocities and accelerations caused by the ship motions. The force \(\vec{F}_k^{(R)}\) describes the static and dynamic forces influencing the agent’s movement on the surface with dynamic inclination while the force \(\vec{F}_k^{(S)}\) is associated with the change of mode of agent movement due to his slip or fall. The non-dimensional factor \(\kappa\) is required for appropriate relative scaling of the physical and social forces.

![Figure 2: Possible movements of an agent](image)

However, direct application the modified SF model as defined by eqs. (2)–(3) is not possible as it may happen that the agent penetrates the obstacle’s boundary if the physical force caused by the local accelerations exceeds the repulsion stemming from the SF potential (Figure 2). It means that in real world the agents would hit rigid boundaries with substantial velocity that may lead to falls and/or injuries. To avoid this, the SF model was complemented with the Reciprocal Velocity Obstacles (RVO) algorithm (van den Berg et al., 2008) which presumes that the agent is being bounced off the rigid boundary resuming his/her advance to the current destination point (see Figure 2).

The resulting simulation algorithm can be described as follows:

1. Determination of current ship displacements, velocities and accelerations.
2. Computation of instantaneous local accelerations for each agent.
3. Assessment of possible motion of each agent taking into account a criterion for keeping upright standing position and presence in view of points of attraction including handrails, bulkheads etc.
4. For each agent capable to advance calculated are current values of the first four terms in eq. (3) in accordance with the current selected path \(M(POI^{in}, POI^{out})\).
5. Calculation of the composite force \(\vec{F}_k\) in equation (3) acting on the agent and determination of the agent’s displacement using eq. (2).
6. Analysis of the intersection of the agents’ trajectories with the boundaries of obstacles. If an intersection is detected the agent is transferred to the intersection and then the actions described in the items 2 through 5 are repeated.
7. If some agent is assessed as disabled and/or cannot continue the advance, he/she is treated as a passive object only subject to gravity, accelerations and friction external forces.

The proposed algorithm is capable to realistically reproduce the effects associated with human movement in a crowd on a moving platform with account for possible incapacitation of the subjects.
3.2 Modeling of sea waves and ship motions

As is clear from the previous subsections, the movements of the agents will depend on the local inclinations and accelerations of the deck beneath the agent. Besides the local coordinates of the agent in the ship-fixed frame, the mentioned local kinematic parameters depend on the ship linear and angular displacements, velocities and accelerations.

Let us suppose that the ship is advancing with the velocity \( \mathbf{V} \) in irregular sea with the general propagation angle \( \chi \) (with \( \chi = 0 \) corresponding to the head sea). The ship seakeeping model is in general 6DOF, the present research is limited with account for only the heave, pitch and roll i.e. \( \ddot{X} = (\zeta, \theta, \varphi) \) while the influence of surge, sway and yaw is neglected. The pitch and roll angle will define the deck inclinations and the local accelerations will depend on the accelerations of the ship and on the local velocities. It is clear that the local linear displacements and velocities of the deck do not affect the motion of the subject. The local acceleration has a tangential component in the deck plane which is pushing the subject while its normal component influences the friction force which is especially essential in the case of wet and slippery deck.

Various seakeeping models can be used for predicting kinematic parameters of ship motions. From the viewpoint of computational efficiency especially attractive are fully linear frequency-domain models which can give reasonably accurate results in moderate sea. In the present study we used the code STRIPmod which is a modification of one of earlier versions of the public linear frequency domain code PDSTRIP (Bertram et al., 2006). However, linear models have certain limitations as they become not accurate at larger roll angles, cannot capture the parametric resonance effects. To obtain more realistic predictions and simulations it is desirable to apply partly or fully nonlinear time domain models such as those described in (Belenky et al., 1998), (Fonseca & Guedes Soares, 2002), (Bezgodov & Esin, 2014) or even models combining seakeeping and maneuvering motions as (Sutulo & Guedes Soares, 2008). A somewhat simplified but nonlinear time domain model was used in our earlier study (Balakhontceva et al., 2015). It can be noted that time domain model have additional capability of capturing gradual changes in the ship hydrodynamic and dynamic properties caused by flooding and raise of the center of gravity when large number of passengers are moving to upper decks possibly impairing the transverse hydrostatic stability.

4 Test Bench and Results

To assure better flexibility and versatility, the developed microscopic evacuation model was embedded into the distributed test bench based on cloud platform CLAVIRE (Knyazkov et al., 2012) which permits combination with various sea spectra and seakeeping codes. This workbench has the ability to transfer the results obtained in the multi-agent simulation environment (Voloshin et al., 2015) in accordance with Figure 3. In addition, the test bench includes visualizer of evacuation processes capable of operating in static or interactive mode. Figure 3 provides an outline of the data flow in the test bench.

Using this software we have studied computational performance of the proposed method. As a test example, considered was the eight passenger decks cruise ship "Costa Allegra" with the following particulars: displacement 28,430m³, length 187.69m, beam 25.75 m, draft 8.20 m, capacity 1,072 passengers (all berths). Cabins are evenly distributed along both sides of the hull. All public places like cafeteria, information desks, and shops are located near the centerplane or on the upper decks of the ship. Numerical experiments were run for three cases of the sea state (5, 7 and 9) and 4 values of the general relative wave direction angle. The initial distribution of passengers and crew was determined in accordance with input data for multi-agent system and depends on age, gender, physical capacities of each agent.
Figure 3: Scheme for the agents’ movement path

Figure 4 shows results obtained for the cases mentioned above. For analysis of the evacuation process we chose kernel density estimation as the main way to estimate the probability density function of an evacuation time which is a random variable. All agents are supposed to start evacuation simultaneously and considered was the so-called "night" scenario when all passengers start from their cabins. The ship is supposed to be stopped but capable to maintain a constant heading with respect to the sea.

![Figure 4: Probability density distributions of evacuation duration](image-url)

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The obtained results demonstrate that the expected evacuation time in general increases with the intensity of ship motions. As could be expected, the most favorable cases are those of head or stern seas and the least favorable is the quartering (60° relative heading), not the beam sea which is typically considered as the most dangerous in stormy conditions. Inspection of data for the ship motions shows that this happens because of unfavorable combinations of accelerations caused by pitch and roll.

5 Conclusions

In our research, we have developed a mechanism fusing a ship motions model with the multi-agent crowd dynamics model in the case of evacuation under storm conditions. The integrated model enables estimation of the evacuation time at various environmental conditions. It can be useful for ship operators and navigators for appropriate planning of evacuation which can reduce possible human losses. The system can be also useful during the design process helping to trace and eliminate possible bottlenecks on the routes to the emergency exits.

The obtained test numerical results show that the proposed method consistently captures main effects associated with passenger movements in storm conditions and can serve as basis for developing on-board Decision Support Systems (DSS). The most popular type of such a system is a visualized polar diagram displaying undesirable combinations of the speed and heading typically using such criteria as the main and parametric roll resonances, slamming occurrence frequency, green water on deck, and propeller ventilation. It will be natural to complement these diagrams with some information related to possible evacuation in current weather conditions. As the developed system is too slow for accelerated online evacuation simulations, the DSS should be rather based on pre-computed quantiles of distributions of local accelerations and inclinations for various ship locations while the evacuation simulation package can help to establish some threshold values for these quantiles above which the evacuation becomes problematic or its expected duration become unacceptable in current circumstances.

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References


