Procedia Computer Science
Volume 66, 2015, Pages 140–149
YSC 2015. 4th International Young Scientists Conference on Computational Science

Multi-agent Simulation of Passenger Evacuation Considering Ship Motions

Marina Balakhontceva[1], Vladislav Karbovskii[1], Dmitrii Rybokonenko[1] and Alexander Boukhanovsky [1]
[1]*ITMO University, Saint Petersburg, Russia*
m.balakhontseva@gmail.com, vladislav.k.work@gmail.com, dmitry.rybokonenko@gmail.com, *avb_mail@mail.ru*,

Abstract

This paper presents a system for multi-agent simulation for passenger evacuation in case of the inclination of a ship under the storm. Evacuation process depends on many different factors such as environmental properties (e.g. wind velocity, intensity of waves), human behavioral aspects and so on. In order to describe passengers' behavior in case of emergency evacuation considering the inclination of a ship, we applied a force-based model adapted from multi-agent system. Our approach provides an opportunity to estimate evacuation time depending on intensity of waves, rate of sailing and relative direction. Our proposed model can be coupled with the simulation of ship flooding or fire propagation. Having analyzed the results, these outputs could be applied to design contingency plans to assist the crew members in the frameworks of decision support systems (DSS).

Keywords: evacuation process, computer simulation, multi-agent models, ship motions, damage stability

1 Introduction

Modern design of passenger ships has lead to increasing size and capacity of vessels, so nowadays ships might carry more people than in XIX century. World Ocean is a very aggressive environment still causing severe difficulties to operation of vessels and marine objects. Though emergency rescue and coast service advanced in safety management, now and then catastrophes occur and some of them take human lives and damage the health. The main reason of human losses is rapid accident propagation. Over the past few decades a number of major disasters involving passenger ships stirred up the public. Some of them claimed the lives of several thousand people, for instance, collision and fire propagation entailed consequent lost of the Dona Paz in 1987 and led to casualties of 4386 lives; wreckage of the Estonia in 1994 caused 852 fatalities; collision of the Admiral Nakhimov in 1986 resulted in 425 human losses. According to the statistics, there were 75 large ship losses only in 2014. Most of losses occurred due to the damages in engine room, fire outbreak and collisions or hull

Selection and peer-review under responsibility of the Scientific Programme Committee of YSC 2015

doi:10.1016/j.procs.2015.11.017

damage (Statista, 2014). Permanent nature of wreckages, challenging environment to save people in the water, and weather conditions, justify the need for the development of complex systems for simulation of passenger evacuation.

To reduce human losses, crew members must take prompt actions to organize the emergency evacuation of passengers. Accordingly, after the great human losses of the Estonia, the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) developed the guidelines for evacuation analysis of Ro-Ro passenger ships (IMO, 2007). These guidelines contain basic information to determine the optimal time and speed of movement for passenger evacuation. Evacuation process depends on many different parameters based on individual characteristics of each passenger, spatial representation of the decks, and location of emergency exits and so on. Contemporary passenger ships are complex engineering objects with multiple technical characteristics, such as tonnage, length, beam, draught, installed power, and capacity. In summary, real data is next to impossible to collect and analyze, so the process of passenger evacuation could be best studied by computer simulation (Mordvintsev, 2014).

In case of emergency evacuation simulation, high-level requirements for crowd motion models should be applied. These models must cover all essential aspects and provide useful information about dynamics of the process itself. Generally, the basis of crowd motion models is intuitive and comprehensible assumptions and rules. Taking into account the application to real world structures and processes, another requirement is flexibility, especially concerning the application to various phenomena and settings or environment (Kluepfel, 2003). In case of maritime accidents, a list of these requirements for simulation application is expanded by another specific parameters coming from ship motions.

For the simulation of an evacuation analysis, technology must take into account (1) spatial model for evacuation analysis, (2) algorithm for evacuation analysis, (3) human behavior under emergency conditions, and (4) impact of ship motions (Lee, 2003).

This article is devoted to multi-agent simulation system for passenger evacuation from damaged ships. This system considers a ship motion model to estimate the impact of marine environment to evacuation process. Our approach provides an opportunity to estimate evacuation time depending on intensity of waves, rate of sailing and relative direction.

2 Related works

Recently, several projects have been devoted to the development of models for evacuation analysis of passenger ships, such as Maritime-EXODUS project of University of Greenwich (Gwynne, 2003) were developed for a full-scale simulation evacuation from damaged ship under fire propagation. The EXODUS platform consists of five major components: velocity-based pedestrian model, population distribution, human behavior model, fire and smoke spreads model, and environmental hazard subprogram.

The main aim of the project IMEX (Park, 2004) was to develop a model able to simulate various evacuation procedures from public transportation systems, e.g. buildings, ships or aircrafts. Based on discrete-cells spatial representation, this model can simulate movements and behavior of each person in the crowd. BY-PASS model (Meyer-König, 2002) offers another solution of intelligent ship evacuation. The model is also marked by general features of evacuation models, dynamic model, and intelligent human behavior model.

In the past decades, scientists tried various approaches to design frameworks for human evacuation. EVAC simulation program (Drager, 2001) used a microscopic method to simulate evacuation process through the interaction between passengers with several individual characteristics. However, dynamic effect and ship motions' characteristics were not included in this model. At the same time, a passenger evacuation simulation system Evi (Vassalos et al., 2003) as a real-time interactive model used a mesoscopic approach. Virtual environment applied to improve efficiency of evacuation performance is a distinctive feature of Evi. Based on multi-agent modeling technique, it is the most appropriate model for passenger evacuation simulation on a multi-level planning structure.

AENEAS (Meyer-König, 2007) model was developed solely for the implementation of ship motions into the framework. Analysis of the simulations showed the influence of ship motions on the results of evacuation process. In this system, reduction coefficients for velocity values in different inclinations of the deck served as input data for evacuation simulation.

Existing solutions in the domain under study only partially regard the impact of the ship motions to the evacuation processes. These approaches consider only the kinematics of ship movements introducing the reduction coefficients for the velocity of passengers. The velocity values of each person in the crowd were calculated for a number of static values of angles of roll or pitch. Having approximated real data from these experiments, reduction coefficients were derived.

It should be noted that considered the velocity of human as a determining factor of his movement is not entirely correct. Cause the nature of human movements is based on the natural (physical) and social forces.

3 System for Ship Evacuation Simulation

3.1 Spatial representation model

Spatial representation of ship is a pseudo three-dimensional continuous space. In other words, space in our multi-agent system (Voloshin, 2015) presented as a set of linked two-dimensional subspaces (decks). Space of each deck consists of obstacles, points of interest (POI), emergency exits and portals between levels (stairs and lifts). Points of interest represented by cabins and public areas like shops and restaurants. Also, there are a graph for path finding and route selection for agents' desired destination. This graph generated by quadtree method for space rasterization. This method allows recursively splitting the space by quadrants with minimal and maximal step. Figure 1 shows a part of generated graph with passenger cabins and stairs.

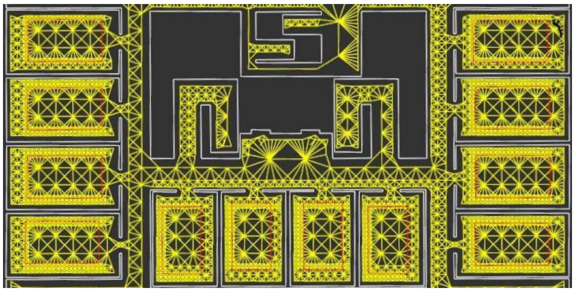

Figure 1: Part of the deck representation

3.2 Crowd model

Crowd modeling is a critical part of evacuation simulation. There are two basic approaches for crowd modeling, macroscopic and microscopic. The first approach describes the crowd like a fluid which follows the flow fluid dynamics principles. In the second approach the flow consist of many separate entities which can interact with each other (Bonabeau, 2002). As mentioned above, physical and social forces underlie human movement. It means that acceleration is a key reason for human movement in a given or desired direction. At the same time the practice of rationing habitability of marine objects (Sarıöz, 2005) shows that the movement of passengers significantly depends not only on a kinematic and dynamic characteristics of ship motions.

Impact of acceleration cannot be directly taken into account by using an evacuation model based on the task velocity distribution law (Van den Berg, 2008). Thus required, an alternative approach in which the rules of the road agents are defined on the basis of power models, for example - a model of social forces (Social Force) (Helbing, 1995). According to this model of pedestrian traffic can be described by three components: the acceleration (deceleration), attraction and repulsion, which are measures of intrinsic motivation person to commit a particular action. In this interpretation, the movement of the passengers on the ship is described as a many-body problem in which the equation of change of speed $\vec{v}_k$ for the *k* individual has the form:

$$m_k \frac{d\vec{v}_k}{dt} = \vec{F}_k(t) + \vec{\varepsilon} \quad (1)$$

Where $\vec{\varepsilon}$ is the random fluctuation associated with the heterogeneity of the population, m_k – the mass of a passenger, and $\vec{F}_k$ is the composite force consist of the following components (Rybokonenko, 2015):

$$\vec{F}_k(t) = \vec{F}_k^{(0)}(\vec{v}_k, v_k^0\vec{e}_k) + \sum_j \vec{F}_{kj}(\vec{e}_k, \vec{r}_k - \vec{r}_j) + \sum_n \vec{F}_{kn}(\vec{e}_k, \vec{r}_k - \vec{r}_n^k) + \sum_i \vec{F}_{ki}(\vec{e}_k, \vec{r}_k - \vec{r}_i, t) + \vec{F}_S \quad (2)$$

In this equation $\vec{e}_k$ – the direction of movement of a person; $\vec{F}_k^{(0)}$ – the force due to proper acceleration; $\vec{F}_{kj}$ – the repulsive interaction force between person *k* and person *j*; $\vec{F}_{kn}$ – the force due to repulsion between agent and obstacle; $\vec{F}_{ki}$ – the attraction force between a passenger and environmental objects like other passengers, handrails and so on; $\vec{F}_S$ – force due to ship motions.

3.3 Ship motions influence model

Ship motions are defined by the six degrees of freedom: three components of translation (heave, sway, surge) and three components of rotation (pitch, roll, yaw). In general terms equation of ship motion forces can be written in the form sum of two components:

$$\vec{F}_s = \vec{F}_k^{(R)}(X, \dot{X}, \ddot{X}) + \vec{F}_k^{(S)}(X, \dot{X}, \ddot{X}) \quad (3)$$

In this expression first term is the force coming from movement of a person by surface with dynamic inclination, second term associated with sliding movement of person. In case of evacuation simulation under the conditions of ship motions we are dealing with non-inertial reference frames. Then Newton's second law in the rotating frame becomes:

$$\vec{F}_k = \vec{F}_{int} + \vec{F}_{cen} + \vec{F}_{cor} + \vec{F}_{eul} + \vec{F}_{grav} \quad (4)$$

First item is the force caused by movement between frames, second force is the centrifugal, third term of equation is the Coriolis force; fourth item is the Euler force. If assume each item in equation (4) as production of mass and acceleration, we obtain new expression:

$$m\vec{a}_r = m\left[\frac{d^2\vec{R}}{dt^2}\right] + m[\vec{\omega} \times [\vec{\omega} \times \vec{r}]] - 2m[\vec{\omega} \times \vec{v}_m] + m\left[\frac{d\vec{\omega}}{dt} \times \vec{r}\right] + m\vec{g} \quad (5)$$

In equation (5) $\vec{R}$ is a distance between two coordinate system (inertial and non-inertial), in case of our model centers of the two coordinate systems are identical and $\vec{R} = 0$; a radius-vector $\vec{r}$ determinate position of an agent; $\vec{\omega}$ is the vector of rotation components; $\vec{v}_m$ is own-agent velocity.

In equation (5) it's necessary to observe the third translation component of ship motions. It should be added these terms to the equation:

$$m\vec{a}_r = m[\vec{\omega} \times [\vec{\omega} \times \vec{r}]] - 2m[\vec{\omega} \times \vec{v}_m] + m\left[\frac{d\vec{\omega}}{dt} \times \vec{r}\right] + m\vec{g} + m\ddot{\zeta} \quad (6)$$

Expression (6) does not include friction force. In our simulation we consider this force like a trigger-function. The trigger condition is maximizing of static friction force:

$$km\vec{g}cos\Theta cos\psi < mg\sqrt{1 - cos^2\Theta cos^2\psi}$$

When the trigger-function is in action agents stop their current activities and change the destination points to the nearest handrails. This activity influence on agents desired position and current velocity.

3.4 Waves propagation model

Key aspect of applicability equations (1-3) is X characteristics of waves. Position of ship with velocity $\vec{V}$ and off-bow angle χ to principal wave direction in fixed frame described three translation and three rotation components. In our research we limited these components to pitch, roll and surge $X = (\zeta, \Theta, \psi)$

The rotation items Θ, ψ identify the slope of decks and accelerations of surge $\ddot{\zeta}$ have an impact on friction force (surface traction) on the move. Accordingly, for the evaluation of these items we used the system of nonlinear equations (Boukhanovsky, 2004):

$$\begin{aligned} &\ddot{\Theta} + 2v_\Theta(V)\dot{\Theta} + n_\Theta^2\Theta f(\Theta)(1 + \vartheta\zeta) = M_{W\Theta}(x, t) \\ &\ddot{\zeta} + 2v_\zeta\dot{\zeta} + n_\zeta^2\zeta - a_{33}V\dot{\psi} - a_{35}V\psi = F_{W\zeta}(\chi, x, t) \qquad (7) \\ &\ddot{\psi} + 2v_\psi(V)\dot{\psi} + n_\psi^2(V)\psi = M_{W\psi}(\chi, x, t) \end{aligned}$$

These equations bring in non-inertial coordinates which not coupled with ship movement. In (7) $F_{W\zeta}(\chi, x, t), M_{W\psi}(\chi, x, t), M_{W\Theta}(x, t)$ are the destabilizing force and the moments caused by waves, these moments depending on camber of wavy surface; $v_\zeta, v_\psi(V), v_\Theta = v_1 + v_2(V)$ are the damping coefficients; $n_\zeta, n_\psi(V), n_\Theta$ – the proper frequencies; a_{33}, a_{35} are the coupling coefficients account for moments of inertia and added-liquid mass. The parameter ϑ report in terms of function $\vartheta = \vartheta(S, z_p)$, where S is waterline area and $z_p = z_c - z_g$ is the center of buoyancy above molded base. The function $f(\Theta)$ set degree of nonlinearity of transverse righting moment and express in terms of ship stability diagram. For sea waves modeling with equation (7) in right part of this used wave spectra which corresponding with characteristics of climate (Boukhanovsky, 2007).

The equation system (7) describe the ship motions under the action of the destabilizing force $F_{W\zeta}$ and the irregular moments $M_{W\psi}, M_{W\Theta}$. These items calculate by forth integration over the wetted surface of the ship. The wetted surface is determined by the ship's position relative to space-time field of sea disturbance $\xi(x, y, t)$. This field solve for modified Longe-Higgins model (Longuet-Higgins, 1969):

$$\xi(x, y, t) = \sum_n a_n \left(cosk_n^{(x)}x + sink_n^{(y)}y - \omega\left(k_n^{(x)}, k_n^{(y)}\right) + \phi_n\right) (8)$$

In this equation $k_n^{(x)}, k_n^{(y)}$ are the wave numbers linked with wave frequency; a_n – the separate harmonic amplitude calculated by energy spectrum; ϕ_n – the random phases. In addition, the items $k_n^{(x)}, k_n^{(y)}$ have random variability inside of discretization interval.

4 Simulation and results

4.1 Input data for simulation

Cruise ship “Costa Allegra” were selected for proposed evacuation simulation. General characteristics of the ship are given in table 1.

Tonnage:	28,43 GT, 11,97 NT 7,39 DWT	Type:	Cruise ship
Length:	187.69 m (615.8 ft)	Decks:	8 (passenger accessible)
Beam:	25.75 m (84.5 ft)	Speed:	19 knots (35 km/h; 22 mph)
Draught:	8.20 m (26.9 ft)	Capacity:	1,072 passengers (all berths)

Table 1: General characteristics of “Costa Allegra”

The ferry has eight passenger decks. Cabins are distributed on both sides of the hull. All public places like cafeteria, information desks, and shops are situated along the center or on the upper decks of the ship. First of all, it’s necessary to interpret the ship definition into a multi-agent system. Therefore, 3d Max model parsed in multi-agent system like a set of lists containing objects and their own coordinates. The objects include obstacles, points of interests (cabins and emergency exits), stairs and lifts (for movement between decks). Also ship model include graph for path finding.

Experiments run on three different cases of the intensity of waves (5, 7, 9 sea forces) and four cases of the rate of sailing (0, 5, 15, 25 knots). The ship has 30 angle degree of relative direction for principal wave direction. This modeling assumption accepts to differentiate between influences of different types of ship motions. The initial distribution of passengers and crew is determined in accordance with input data for multi-agent system and depend on age, gender, physical capacities of each agent.

4.2 Proposed algorithm

Consequently, for solve problem of passenger evacuation computational modeling in case of the ship motions we combined three different models. At the first stage, it’s necessary to set the wave energy spectrum for calculation space-time field of sea disturbance in equation (8). Then the destabilizing force and the moments calculated for equations (7). These data considered for forces calculation in expression (2) and (3). Outputs from function (2) used in equation (1).

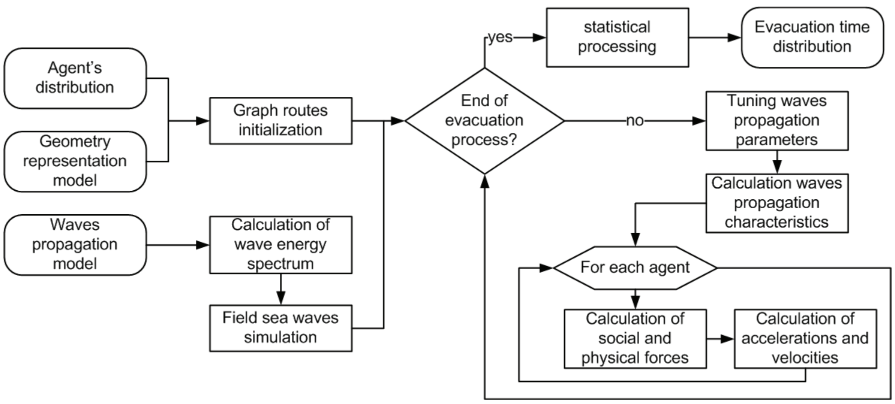

Figure 2: Schema of simulation process

Evacuation begins at the same time for all agents. Each agent can be initialized in the system only for a definite POI. After start of the evacuation each agent tries to find the shortest path to emergency exit. The path finding algorithm minimizes the evacuation time. Figure 2 gives a general schema of simulation process.

4.3 Experimental scenario and results

For description of proposed experimental scenario we must take into account several assumptions:

- all agents start evacuation at the same time;
- all agents are in cabins (two persons per cabin in average);
- evacuation is completed if an agent has reached the destination point (emergency exit), which situated on each deck;
- evacuation is failed if an agent can't find current path several iterations at a run;

In this section we present some experimental results. Proposed agent-based simulation environment used data from sea wave's propagation model (see Fig. 2). There were four modes of simulation with different vessel speeds (0, 5, 10, 15 knots). It means that evacuation process started when a passenger ship move at a certain speed and during emergency situations this speed is maintained. Each mode includes four intensities of waves (0, 5, 7, 9 points). Each mode runs 100 times with 500 agents in simulation. Table 2 gives the main characteristics of sea waves.

Intensity of waves, points	Wave height, m	Wave average period, s	Wave average length, m
5	2 – 3.5	7	50
7	6 – 8.5	10	100
9	11 and more	16	250

Table 2: Characteristics of seaways

Figure 3 get results of four cases of evacuation simulation. For analysis of evacuation process we chose kernel density estimation as a main way to estimate the probability density function of an evacuation time (random variable). In figure 3 (a) tail of distribution becomes lengthen and peak of distribution smoothen while storm force increasing. Vessel speed practically has no effect to kernel density estimation for seaways with 5 points.

The reason is that values of roll and pitch angles are insignificant. In case of 7 points of wave's intensity we came to the conclusion that optimal value for vessel speed is 10 knots. As can be seen from figure 3, the speed of vessel also has a major impact for evacuation process under the storm with described above characteristics of environment. But it's necessary to include another criterion for more accurate estimate of evacuation process from damage ship. Therefore, we conducted a comparative assessment of evacuate agents. For this purpose, data of numbers of survival agents was collected.

Figure 4 present a kernel density distribution for survival agents in percent. Given these data, our conclusions about figure 3 become uncertain. Shifts and flattening of peaks (see Figure 4 (b), (c), (d)) of distributions are a reflection of the fact that in these cases near the emergency exits and corridors accumulates more agents and formed crush. This occurs because values of ship motions are reduced and agents don't change their points of destination from exits to handrails. It means that agents can move and follow to main evacuation goal.

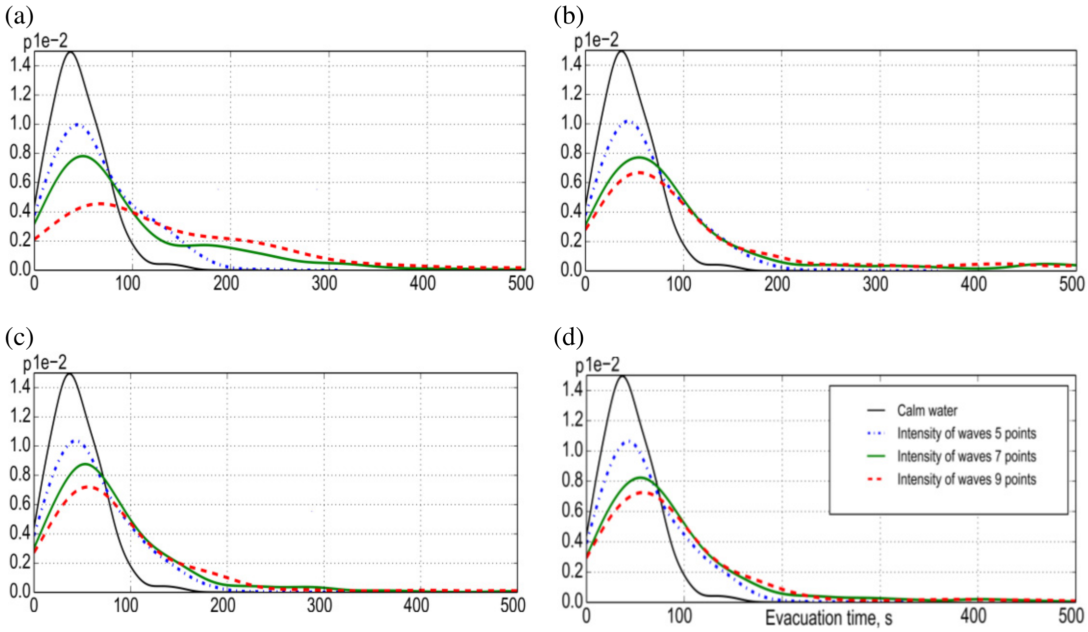

Figure 3: Kernel density distributions of evacuate agents for (a) 0 knots, (b) 5 knots, (c) 15 knots, (d) 25 knots

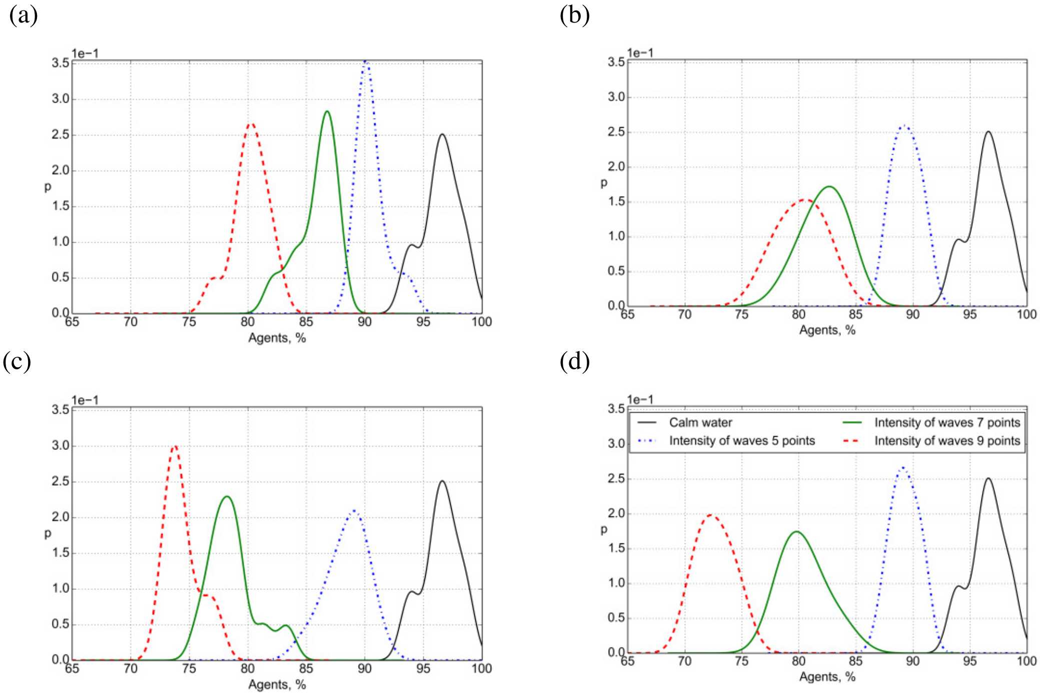

Figure 4: Kernel density distributions of evacuate agents for (a) 0 knots, (b) 5 knots, (c) 15 knots, (d) 25 knots

5 Conclusions and future work

In our research we evaluate the mechanism for integration several characteristics of ship motions in pedestrian dynamic model in case of evacuation. We have developed the multi-agent model for simulation of evacuation processes considering ship motions. Our model allows to estimate evacuation time depend on environmental conditions. It can be useful for ship driver to hold down the lossless. Also it will be helpful for crew members to reduce human losses and take prompt actions to organize the emergency evacuation process. In terms of ship design, this model could be useful for identification of potential bottlenecks on the way to the emergency exits.

The most difficult tasks in multi-agent modeling of social systems are verification and validation of such models. Due to large limitations in implementation of a real-life experiment and capturing real data, in some cases researchers will rely only on assumptions and guesses. Our system has the visualization sub-system to assess the evacuation process. Visualization helps to understand some specific details of ship motion influence.

In future we plan to add in spatial representation model a mustering areas (special POI), and split all agents to several groups. The division into groups will occur according to the degree of awareness of accident propagation. Each group will have unique options and mechanism for knowledge acquisition. Another future plans' direction refers to implementation of fire propagation and flooding scenarios. Also it's very important to research influence of general direction on evacuation process.

Evacuation analysis of ship requires some specific actions than in cases on the ground because ships are surrounded by water. The passengers and crew should be ensured lifejackets and lifeboats for moving away from the ship safety. This major aspect should be taken into account in the design systems for ship evacuation simulation.

Acknowledgements

Theoretical studies in this paper are financially supported by Ministry of Education and Science of the Russian Federation, grant proposal #2015-14-588-0003-4183. Experimental research in this paper is financially supported by The Russian Scientific Foundation, Agreement #14-21-00137 (15.08.2014).

References

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*,*99*(suppl 3), 7280-7287.

Belenky, V. L., Degtyarev, A. B., & Boukhanovsky, A. V. (1998). Probabilistic qualities of nonlinear stochastic rolling. *Ocean Engineering*, *25*(1), 1-25.

Boukhanovsky, A. V., Lopatoukhin, L. J., & Soares, C. G. (2007). Spectral wave climate of the North Sea. *Applied Ocean Research*, *29*(3), 146-154.

Boukhanovsky, A., Ivanov, S., Nechaev, U. (2004). Virtual modeling of ship motions dynamic in intelligent simulators. In *Artificial intelligence* 2004 (3). *pp*. 350—359, printed in Russian

Drager, K. H., Orset, S., 2001. EVAC—the mustering and evacuation computer model resulting from the BriteEuram project MEPdesign. *Proceedings of Conference on Pedestrian and Evacuation Dynamics*, pp. 355–368

Gwynne, S., Galea, E. R., Lyster, C., & Glen, I. (2003). Analysing the evacuation procedures employed on a Thames passenger boat using the maritimeEXODUS evacuation model. *Fire technology*, *39*(3), 225-246.

Helbing, D., & Molnar, P. (1995). Social force model for pedestrian dynamics.*Physical review E*, *51*(5), 4282.

IMO, 2007. MSC.1/Circ.1238, Guidelines for Evacuation Analysis for New and Existing Passenger Ships. [Online]Available at: http://www.imo.org [Accessed 1 September 2009]

Kluepfel, H. L. A cellular automaton model for crowd movement and egress simulation : дис. – Universität Duisburg-Essen, Fakultät für Physik, 2003.

Lee, D., Kim, H., Park, J. H., & Park, B. J. (2003). The current status and future issues in human evacuation from ships. *Safety Science*, *41*(10), 861-876. Review

Meyer-König, T., Klüpfel, H., & Schreckenberg, M. (2002). Assessment and analysis of evacuation processes on passenger ships by microscopic simulation. *Schreckenberg and Sharma [2]*, 297-302. BY-PASS

Meyer-König, T., Valanto, P., & Povel, D. (2007). Implementing ship motion in AENEAS—model development and first results. In *Pedestrian and evacuation dynamics 2005* (pp. 429-441). Springer Berlin Heidelberg.

Park, J. H., Lee, D., Kim, H., & Yang, Y. S. (2004). Development of evacuation model for human safety in maritime casualty. *Ocean engineering*, *31*(11), 1537-1547. *IMEX*

Sarıöz, K., & Sarıöz, E. (2005). Habitability assessment of passenger vessels based on ISO criteria. *Marine Technology*, *42*(1), 43-51.

Statista, *web-resource*, http://www.statista.com/chart/3354/large-ship-losses-reach-lowest-point-in-a-decade

Van den Berg, J., Lin, M., & Manocha, D. (2008, May). Reciprocal velocity obstacles for real-time multi-agent navigation. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on* (pp. 1928-1935). IEEE.

Vassalos, D., Guarin, L., Vassalos, G. C., Bole, M., Kim, H., & Majumder, J. (2003). Advanced Evacuation Analysis–Testing the Ground on Ships. In *Proceedings of the 2nd international conference on pedestrian and evacuation dynamics*.

Longuet-Higgins, M.S., (1969), A non-linear mechanism for generation of sea waves, "*Proc. Roy. Soc*", 1969, Ser. A 311, pp. 371-389

Mordvintsev, A.S., Krzhizhanovskaya, V.V., Lees, M.H., Sloot, P.M.A. (2014). Simulation of City Evacuation Coupled to Flood Dynamics. In book: "Pedestrian and Evacuation Dynamics 2012". U. Weidmann, U. Kirsch, M. Schreckenberg (Eds.) Springer, 2014, XXIV, pp. 485-499. http://dx.doi.org/10.1007/978-3-319-02447-9_40

D. Rybokonenko and V. Karbovskii, *"Social force lib,"* GitHub repository, 2015. [Online]. Available: https://github.com/itmo-escience/social-phys-lib.

Voloshin D., Rybokonenko D., Karbovskii V. Towards a Performance-realism Compromise in the Development of the Pedestrian Navigation Model //Procedia Computer Science. – 2015. – T. 51. – C. 2799-2803.