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Agent-based Modeling of Crowd Dynamics on a Moving Platform

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Abstract
This paper proposes a mathematical model and a computational approach applied to the study of the interaction between a moving platform and pedestrians walking on it. A ship deck motion used as a basic scenario for simulation is realized in three modes reproducing heaving, pitching or rolling rotations of the vessel. Behavior of virtual passengers is emulated by the Social Force pedestrian model modified with additional forces. In this paper the mathematical definitions of both models and their software implementations are discussed. The results of the experiments reproducing various combinations of characteristics of the ship motion are presented and compared with a case where it remained stationary. The paper is concluded with an analysis of the simulation results and perspectives for further research.

Keywords: agent-based modeling, crowd simulation, moving platform

1 Introduction & Related works

The problems of moving and tilted environments and their interactions with human beings have been in focus of researchers and practitioners in various fields for quite a long time. However, it was not until recently that specialists received tools and access to robust data in order to quantify and model the observed effects. Today, several fields of research could be identified where these problems receive significant attention: marine engineering and safety studies; civil engineering (design of residential constructions and footbridges); aircraft design and evacuation studies; railroad evacuation and carriage design.

In the domain of sea craft engineering and safety, one of the key issues is to analyze the effects that normal and extreme accelerations of the craft have upon the crew of the vessel and passengers (in cases of the civil fleet research). The exposure of the crew to vessel motion is investigated from the perspective of member's ability to maintain postural stability, perform key activities without stopping (due to the so-called Motion Induced Interruptions [1]) and withstand associated factors such as

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motion-induced fatigue [2] that may result in an increased number of accidents onboard the ship. The analysis of the secondary data (namely, reports of the actual accidents that took place, for instance, as in [3]) that was, for a long time, a predominant technique, has been recently complimented by the introduction of advanced sensors [4], experiments [5] [6] and modelling [7]. Recent studies have as well incorporated the use of interviewing for studying long-term adaptation to the aforementioned effects and assessing the role of additional factors, such as vibrations and noise [8].

Investigation of the ship motion-related effects on the behavior of passengers predominantly focuses on the evacuation process. Up to date there has been a large number of works dedicated to experimental studies of the evacuation process from ships [9] [10] [11]. Existing research vary in scale and initial conditions, but as Kim et al [12] and [13] illustrates, they partially agree on the dynamics of change of the mean individual walking speed and other factors relevant to evacuation dynamics. However, only a modest proportion of such studies actually takes into account various factors associated with crowd behavior (particularly, they are addressed in [10]).

Building upon the experimental data and real-world observations, researchers in the field of marine engineering and safety develop evacuation simulators in order to conduct cost-effective full-scale tests to be run at the early stages of ship and evacuation strategies design. The algorithms for simulating the evacuation of passengers from ships are transferred from the relevant research dealing with the evacuation from the stationary constructions. To our knowledge, it was not until 1998 that computational models started to take into account ship motion and tilt angles when simulating human behavior on board sea and ocean crafts [14]. Nowadays quite a few models incorporate ship motion and inclination modules into the simulation of ship evacuation.

In Kostas et al [15] a similar differentiation-based ship motion model is used, but it has fewer components, compared to the one described in this paper: it lacks Coriolis Force and the vertical acceleration of the ship – heave both realized in the model described here. The pedestrian model described therein resembles the RVO model, which has not been stated directly in the paper – it does not distinguish between obstacles and other agents and it is found to be less realistic compared to the Social Force pedestrian model. At the same time, it is more complicated on the side of different types of group aligning behavior accounted for and contextual embeddedness of the behavioral rules that agents follow. Pennycot and Hifi [16] in their paper focus the attention on the evacuation procedures in extreme conditions – where critical inclination angles (with the resulting stabilization of agents posture being considered) of the ship and fire are simulated as potential threats to the passengers. It is designed specifically for risk evaluation in different scenarios: one of the components of the system is represented by the outline of the ship with a route graph connecting the initial locations of the passengers, cabins, doors, passages, exits etc. In this sense, the scope of application of the model described here is somewhat broader as simulation modules are context-independent thus can be easily extended with additional models of hazards like it has been illustrated in [17] [18]. The evacuation model coupled with ship motion dynamics described in [19] is based on cellular automata for reproducing the movements of passengers aboard the ship. Though the proposed approach is more effective from the performance point of view – it has significant limitations on the realism side [20], which shall be taken into account when plausibility of simulation results is of higher priority than processing speed.

It has been found that studies accounting for evacuation process from the angled passenger vehicles [21] in accidents are very similar to the ones conducted in the field of ship motion-induced effects on passengers and the crew. However, after a closer examination, it became obvious that in the field of railroad evacuation the characteristics of the moving carriage is of little interest – the accent is shifted towards the changes in navigation that angled and unfamiliar environment brings into the process of evacuation.

In the field of civil engineering, the interest towards the effects that the motions of the environment have upon human beings is concentrated on such issues as physical interaction between pedestrians and the man-made infrastructural objects they are walking across (and particularly, synchronization effects [22]), influence of structural motions caused by external forces [23] and many others. However, these directions of research are intentionally left outside the scope of this review. The reason is straightforward: despite the vibrations of the very limited range, these studies actually do not deal with moving environments and objects, at least those that can alter the behavior of people significantly.

2 Model description

As it has been described above, the simulation of moving environments requires the reproduction of the inclination angles of the platform and its rotation replicating reciprocating motion. These two aspects require proper considerations on the side of introducing degrees of freedom. In order to thoroughly reproduce the motion of the platform in space, six degrees of freedom are required: three rotational degrees (pitch, roll, and yaw) and three translational ones (to move forward/backward, up/down, left/right in Cartesian three-dimensional system coordinates). For the simulation of the motion of the ship deck in the reference case, three degrees of freedom were implemented – two rotational (pitch and roll) and a single translational (vertical movement). The following is the description of the underlying algorithm and details of its realization.

In general, the algorithm for calculating the forces affecting the agent during pitching consists of the following steps:

1. Definition of the position and speed of the agent in the platform coordinates.
2. Adjustment of the coordinate system of the platform to a fixed set of coordinates.
3. Calculation of the acceleration's impact on the agent in a fixed coordinate system.
4. Estimation of the position of the agent at time t_1
5. Redefinition of the position and speed in the platform coordinates.

2.1 Implementation

The component of the model that administers the locomotion of pedestrians is based on the Social Force algorithm [15] presented by Helbing [24]. The rationale behind the choice of the basic pedestrian simulator was to implement the most realistic yet balanced model (in this sense, Social Force has been found more preferable than RVO or lattice gas models, see [20] for the comparison of these models). Forces affecting the agent are defined through the following expression:

$$\vec{F}_\alpha(t) = \vec{F}_\alpha^0(\vec{v}_\alpha, v_\alpha^0 \vec{e}_\alpha) + \sum_\beta \vec{F}_{\alpha\beta}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_\beta) + \sum_B \vec{F}_{\alpha B}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_B^\alpha) + \sum_i \vec{F}_{\alpha i}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_i, t) \tag{1}$$

- $\vec{F}_\alpha^0(\vec{v}_\alpha, v_\alpha^0 \vec{e}_\alpha)$ – acceleration term, which describes pedestrian's tendency to go to desired location, this force is pointing towards that location.
- $\sum_\beta \vec{F}_{\alpha\beta}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_\beta)$ – repulsive effect of other pedestrians.
- $\sum_B \vec{F}_{\alpha B}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_B^\alpha)$ – repulsive effect of borders, $\vec{r}_B^\alpha$ denotes the location of nearest border's piece.
- $\sum_i \vec{F}_{\alpha i}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_i, t)$ – attractive effect, increasing with time t.

The necessity of an additional component to the resulting force has been established empirically throughout the attempts to model the influence of the platform motion on the agents' relocations. In case of simulation of agent motion on the moving platform we cannot use Newton's second law directly for calculation of the forces acting on the mass point. Accordingly, it is necessary to take advantages of relative motion kinematics [25]. It means that we can use equation for acceleration formulation in non-inertial frame with one assumption: zeros points of inertial and non-inertial frames of reference situate in one point. Consequently, the acceleration of mass point observed in the fixed coordinate system is given by following expression:

$$\vec{a}_r = \dot{\vec{V}} + \vec{\omega} \times \left[\vec{\omega} \times \vec{R}\right] + \left[\dot{\vec{\omega}} \times \vec{R}\right] - 2[\vec{\omega} \times \vec{v}_m] \tag{2}$$

The present formalization results from the introduction of the gravity force into the model, which has been done in order to make it more physically sound. In equation (2), $\dot{\vec{V}}$ characterizes the transition from the fixed to the rotating coordinate system and in the case described herein, it equals zero. Simulation of moving platform involves three translational degrees of freedom which conditions the need to account for the relevant accelerations. However, we have another one assumption for translational motion. In our model we consider only third translation component because this parameter have most impact on pedestrian locomotion. Finally, the expression for an acceleration of mass point looks the following way:

$$\vec{a}_r = \vec{\omega} \times \left[\vec{\omega} \times \vec{R}\right] + \left[\dot{\vec{\omega}} \times \vec{R}\right] - 2[\vec{\omega} \times \vec{v}_m] + \vec{g} + \ddot{\zeta} \tag{3}$$

Where:

a. $m\vec{\omega} \times \left[\vec{\omega} \times \vec{R}\right]$– centrifugal force, which depends on the platform rotation vector $\vec{\omega}$ (4) and radius vector $\vec{R}$ (10) of the agent. The rotation vector $\vec{\omega}$ can be written as

$$\vec{\omega} = \begin{pmatrix} \dot{\Theta} \\ \dot{\psi} \\ 0 \end{pmatrix} \tag{4}$$

where $\dot{\Theta}$ and $\dot{\psi}$ – pitch and roll platform angles, respectively.

b. $m\left[\dot{\vec{\omega}} \times \vec{R}\right]$ – the inertial force caused by uneven rotation. $\dot{\vec{\omega}}$ is the first derivative of the rotation vector (4).

c. $2m[\vec{\omega} \times \vec{v}_m]$ – Coriolis force, which depends on $\vec{v}_m$ – resulting agent velocity (9) after the calculation of the remaining forces.

d. $m\ddot{\zeta}$ – force caused by vertical movement of the platform. $\ddot{\zeta}$ is acceleration of vertical movement of the platform.

Forces affecting the agent while pitching are processed according to the following formula:

$$\vec{F}_{\alpha p}\left(\vec{r}_\alpha, \vec{\omega}, \ddot{\zeta}\right) = m\vec{a}_r \tag{5}$$

The model agents have no mass, in the final model therefore no need for a gravitational constant g. So within the framework of our extension of social model traffic agents have been incorporated for the simulation. For each agent α relocations are calculated according to the formula:

$$\vec{F}_\alpha(t) = \vec{F}_\alpha^0(\vec{v}_\alpha, v_\alpha^0\vec{e}_\alpha) + \sum_\beta \vec{F}_{\alpha\beta}\left(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_\beta\right) + \sum_B \vec{F}_{\alpha B}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_B^\alpha) + \sum_i \vec{F}_{\alpha i}(\vec{e}_\alpha, \vec{r}_\alpha - \vec{r}_i, t) + \vec{F}_{\alpha p}(\vec{r}_\alpha, \vec{\omega}, \ddot{\zeta}) \tag{6}$$

2.2 System of coordinates

All forces are given in a fixed system of coordinates. To calculate the forces acting on the agent during pitching, it is necessary to move from a fixed coordinate system (*x*, *y*, *z*) to the coordinate system of the platform (χ, μ, η) (mobile).

To do so, using polar coordinates (the radius vector and the angle of deflection of alpha relative to the moving coordinate system) the position of the agent on the platform is determined in the coordinates of the moving frame of reference:

$$\vec{r}\,' = \begin{pmatrix} \chi \\ \mu \\ \eta \end{pmatrix} \tag{7}$$

The speed of the agent (the first derivative of the radius vector of the time) in the coordinates of the moving system:

$$\vec{v}_m' = \begin{pmatrix} \dot{\chi} \\ \dot{\mu} \\ \dot{\eta} \end{pmatrix} \tag{8}$$

The speed of the agent $\vec{v}_m'$ can be represented by velocity of the agent. The presented formula (8) determines the forces affecting the agent with respect to the moving coordinate system of the platform.

Next, we need to calculate the force relative to the fixed frame of reference. Agent speed can be written as

$$\vec{v}_m = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \dot{\chi} cos\psi + \dot{\eta} sin\psi \\ \dot{\mu} cos\Theta + \dot{\eta} sin\Theta \\ \dot{\eta} cos\Theta - \dot{\mu} sin\Theta + \dot{\eta} cos\psi - \dot{\chi} sin\psi \end{pmatrix} \tag{9}$$

$$\vec{R} = \begin{pmatrix} \chi cos\psi + \eta sin\psi \\ \mu cos\Theta + \eta sin\psi \\ \eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi \end{pmatrix} \tag{10}$$

Thus we have acquired the speed (9) and position (10) of the agent relative to the fixed coordinate system, expressed in terms of coordinates of the movable frame.

The next step is the calculation of each element of the main formula:

a. Centrifugal force

$$\begin{aligned} \vec{\omega} \times [\vec{\omega} \times \vec{R}] &= \begin{pmatrix} \dot{\Theta} \\ \dot{\psi} \\ 0 \end{pmatrix} \times \left[\begin{pmatrix} \dot{\Theta} \\ \dot{\psi} \\ 0 \end{pmatrix} \times \begin{pmatrix} \chi cos\psi + \eta sin\psi \\ \mu cos\Theta + \eta sin\psi \\ \eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi \end{pmatrix} \right] = \\ &= \begin{pmatrix} \dot{\Theta} \\ \dot{\psi} \\ 0 \end{pmatrix} \times \begin{pmatrix} \dot{\psi}(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) \\ -\dot{\Theta}(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) \\ \dot{\Theta}(\mu cos\Theta + \eta sin\psi) - \dot{\psi}(\chi cos\psi + \eta sin\psi) \end{pmatrix} = \\ &= \begin{pmatrix} \dot{\psi}(\dot{\Theta}(\mu cos\Theta + \eta sin\psi) - \dot{\psi}(\chi cos\psi + \eta sin\psi)) \\ -\dot{\Theta}(\dot{\Theta}(\mu cos\Theta + \eta sin\psi) - \dot{\psi}(\chi cos\psi + \eta sin\psi)) \\ -\dot{\Theta}^2(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) - \dot{\psi}^2(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) \end{pmatrix} \end{aligned} \tag{11}$$

b. Inertial force caused by uneven rotation

$$[\dot{\vec{\omega}} \times \vec{R}] = \begin{pmatrix} \ddot{\Theta} \\ \ddot{\psi} \\ 0 \end{pmatrix} \times \begin{pmatrix} \chi cos\psi + \eta sin\psi \\ \mu cos\Theta + \eta sin\psi \\ \eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi \end{pmatrix} = \begin{pmatrix} \ddot{\psi}(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) \\ -\ddot{\Theta}(\eta cos\Theta - \mu sin\Theta + \eta cos\psi - \chi sin\psi) \\ \ddot{\Theta}(\mu cos\Theta + \eta sin\psi) - \ddot{\psi}(\chi cos\psi + \eta sin\psi) \end{pmatrix} \tag{12}$$

c. Coriolis force

$$2\vec{\omega} \times \vec{v}_m = 2\begin{pmatrix} \dot{\Theta} \\ \dot{\psi} \\ 0 \end{pmatrix} \times \begin{pmatrix} \dot{\chi}cos\psi + \dot{\eta}sin\psi \\ \dot{\mu}cos\Theta + \dot{\eta}sin\Theta \\ \dot{\eta}cos\Theta - \dot{\mu}sin\Theta + \dot{\eta}cos\psi - \dot{\chi}sin\psi \end{pmatrix} = \begin{pmatrix} 2\dot{\psi}(\dot{\eta}cos\Theta - \dot{\mu}sin\Theta + \dot{\eta}cos\psi - \dot{\chi}sin\psi) \\ -2\dot{\Theta}(\dot{\eta}cos\Theta - \dot{\mu}sin\Theta + \dot{\eta}cos\psi - \dot{\chi}sin\psi) \\ 2\dot{\Theta}(\dot{\mu}cos\Theta + \dot{\eta}sin\Theta) + 2\dot{\psi}(\dot{\chi}cos\psi + \dot{\eta}sin\psi) \end{pmatrix} \quad (13)$$

d. Vertical movement of the platform

$$\ddot{\zeta} = \begin{pmatrix} 0 \\ 0 \\ \ddot{z} \end{pmatrix} \quad (14)$$

Next, a similar $\vec{R}$ (10) at time $t_1 = t_0 + \Delta t$ needs to be calculated and transferred to $\vec{R}'(7)$ again to estimate the force acting on the agent during the ship rolling motion. On the next iteration of the simulation, updated motion data are used in order to model platform dynamics and relocations of agents.

3 Results

3.1 Visual trajectory analysis

As it has been stated above, the aim of the paper is to study the effect that the pitching of the mobile platform has upon the locomotion of people walking it. A model based on Social Force method has been implemented to simulate the movement of the pedestrians. Three degrees of freedom have been introduced to the model in order to reproduce the accelerations of the platform: pitch, roll and heave. The combinations of various values of these characteristics of platform's motion have been trailed for five basic scenarios (see Fig. 1).

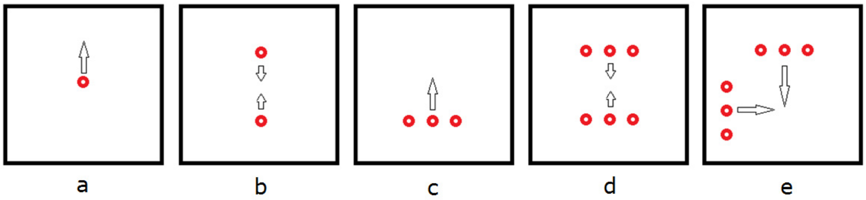


Figure 1 Simulation scenarios

In the first scenario (Fig. 1a), the movement of a single agent towards a defined destination on a platform is simulated. The second example (Fig. 1b) has been extended and thus replicates the movement of the two agents towards each other. The third scenario (Fig. 1c) deals with a triad of agents walking the same direction, whereas in the fourth one (Fig. 1d), the movement of two groups of agents towards each other can be observed. Finally, the fifth scenario (Fig. 1e) has been built around the movement of two groups of agents with perpendicularly intersecting paths.

Some of the degrees of freedom that were implemented for the simulation of ship motion are rotational (pitch and roll) and one is translational (heave). Each degree of freedom has varying properties - the amplitude of the oscillation and period. Moreover, platform fluctuates harmonically using the appropriate parameters (Table 1). Values of 10 and 20 in increments of 2 were used as the

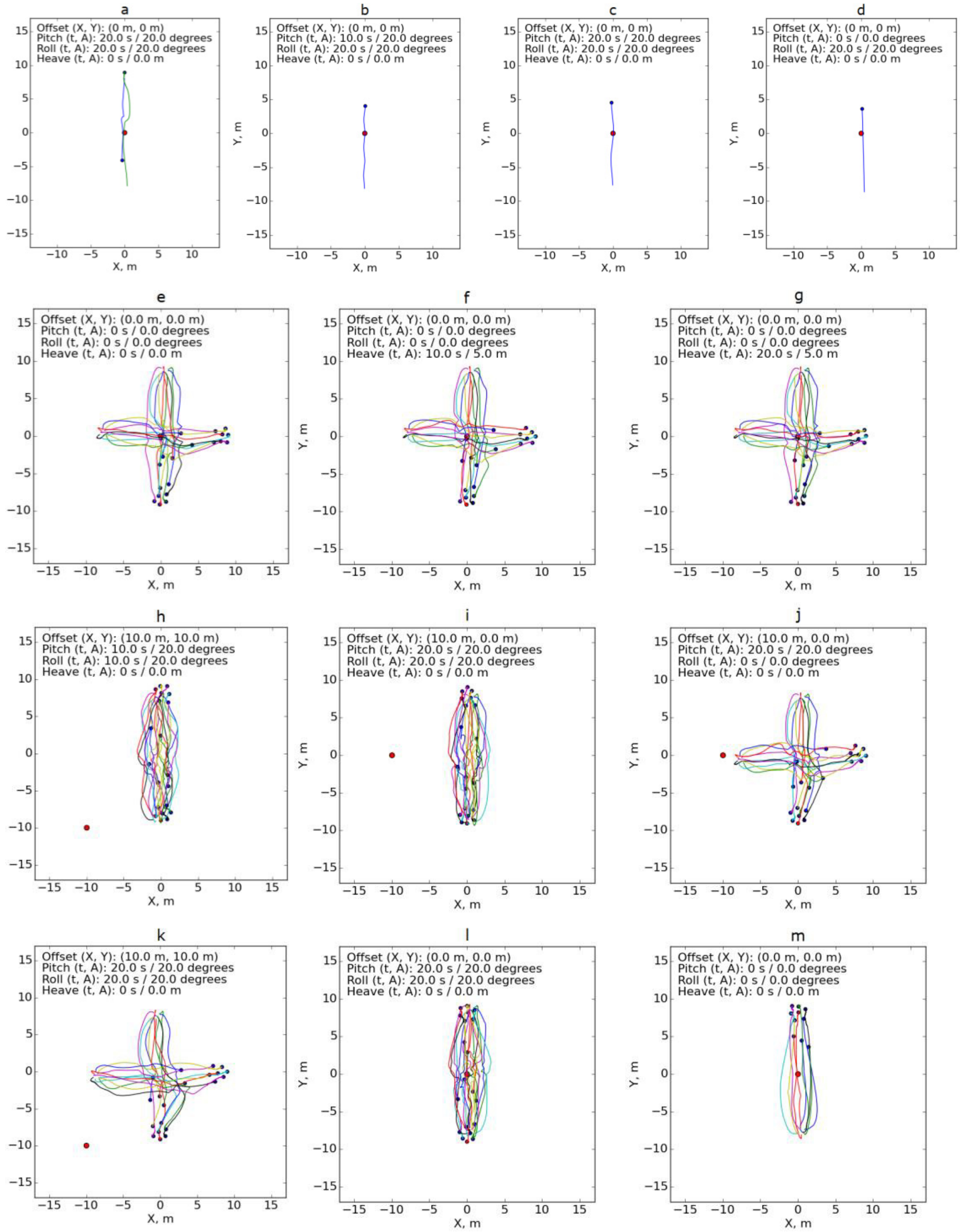


Figure 2 Trajectories of agents

minimum and maximum periods respectively for all implemented degrees of freedom. To specify the range of values of the oscillation amplitude platform we used the values from 0 to 20, with an interval of 2. Finally, the center of the platform has been offset for values in the range of from 0 to 25 in increments of 5.

Name	Units	Min	Max	Step
Roll, Period	Seconds	10	20	2
Roll, Amplitude	Degrees	0	20	2
Pitch, Period	Seconds	10	20	2
Pitch, Amplitude	Degrees	0	20	2
Heave, Period	Seconds	10	20	2
Heave, Amplitude	Meters	0	5	2
Offset, X	Meters	0	25	5
Offset, Y	Meters	0	25	5

Table 1: Experiment parameters

From the analysis of the results of the experiments, a number of conclusions on the role and the significance of each of the components involved into simulation have been drawn. First of all, an assumption that is commonly made in the literature on ship motion simulation – that heave has minor effect on the performance and movement of individuals aboard the ship – has been confirmed. Thus only an insignificant deviation from the predetermined path has been noticed during heaving (see Fig. 2a, b, c). At the same time, pitching and rolling have been found to affect the trajectory of agents greatly in the following way: (a) the trail of agent's relocations tends to stretch on X and Y axes (see Fig. 2d); (b) a deviation from the predefined path has been witnessed when agent moves along one of the axes (see Fig. 2e); (c) an increase in the platform motion angle provides a rise in the oscillation wavelength when the form of these oscillations is close to a sine wave (see Fig. 2e, f).

In relation to the offset variation, the following results have been acquired: (a) an increase in the oscillation amplitude of agents relative to this axis when the distance from the offset center and platform oscillation relative to the selected axis (see Fig. 2h, i, j, k); (b) it has been as well concluded that there is no deviation from the trajectory when agents are moving perpendicular to the axis around which the platform oscillates (see Fig. 2g); (c) considering the comparison of individual and group relocations, it has been found that there is no significant difference between the settings (see Fig. 2f, g, l, m).

3.2 Evacuation use case

The following experimental scenario has been reproduced in the simulations aimed at studying the effect of pitching on the evacuation dynamics: collective abandonment of the compartment through a narrow ("bottleneck") passage (Fig. 3). Red square denotes the area where a total of 100 agents were spawned. The initial coordinates of these “spawn points” are assigned randomly and individually for each agent. Agents are generated simultaneously and as soon as the population is spawned, the crowd starts moving to the final position, located in another room.

The parameters used in the simulation have been estimated close to the real roll of the ship [26]. Each of the scenarios comprising a particular set of parameters has been tested through a series of 20 experimental runs. The table error bars (see Table 2) represent the dispersion of values for evacuation time.

Summarizing the outcomes of the evacuation trials, the following conclusions have been drawn. The employment of heave in the simulation has not led to any significant changes in the monitored output of model. In contrast, pitching and rolling of the ship both increase the total evacuation time, as agents are forced to deviate from the desired path – the one that ensures minimum evacuation time. Moreover, an increase in the offset parameter of the platform motion (for each of the axes) boosts the

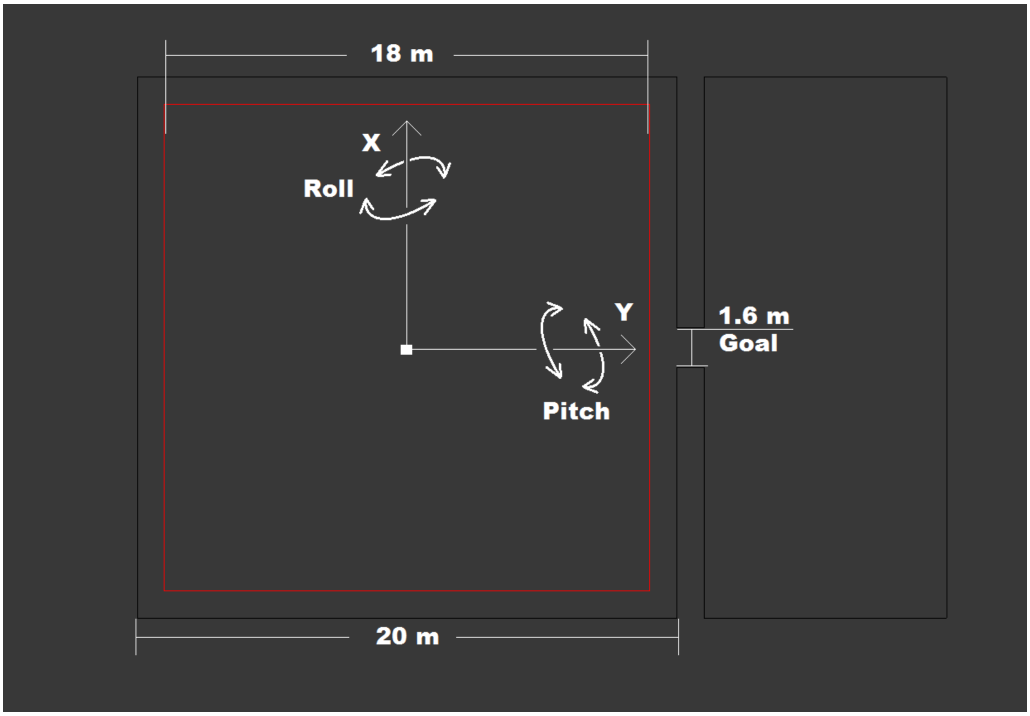
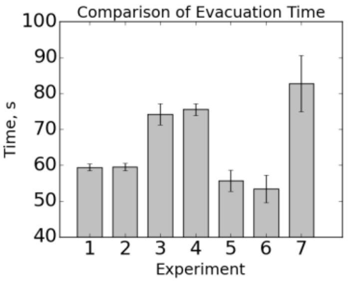


Figure 3 Environment scheme

amplitude of its oscillations, which leads to even greater deviation from agent's intended route thus slightly lowering the overall speed of evacuation.

Parameter	Units	Experiments						
		1	*2*	*3*	*4*	*5*	*6*	*7*
Pitch, Period	Seconds	0	0	5	5	0	0	5
Pitch, Angle	Degrees	0	0	10	10	0	0	10
Roll, Period	Seconds	0	0	0	0	5	5	5
Roll, Angle	Degrees	0	0	0	0	10	10	10
Heave, Period	Seconds	0	5	0	0	0	0	5
Heave, Amplitude	Meters	0	10	0	0	0	0	10
Offset, X	Meters	0	0	0	10	0	0	10
Offset, Y	Meters	0	0	0	0	0	10	10

Table 2: Experiment parameters set



All of the calculations have been performed using the computational unit with the following setup: CPU: Intel Xeon CPU E7-2830, Processor Base Frequency: 2.13 GHz, Max Turbo Frequency: 2.4 GHz, Number of cores: 8, Number of threads: 16, RAM: 128 Gb, OS: MS Windows Server 2012 R2 Datacenter.

4 Discussion and conclusion

In this paper we have presented first results of the development of a Social Force-based computational pedestrian model, expanded with an additional acceleration component determined by the motion of the platform that agents are walking on (available online [27]). Despite the limits that current realization of the model imposes upon the reproduction of degrees of freedom, we assume that it exhibits the ability to facilitate plausible replication of behavior of passengers in a moving elevator or aboard the ship.

Reflecting upon the observed results, the simplicity of the studied scenarios is worth additional consideration as their primary goal was to facilitate the assessment of the reaction of the model to alteration of key parameters (both platform- and agent-related). Since the interior of the marine craft is far more complex than in the presented experimental setting, we are looking forward to reproducing the geometry of a particular functioning vessel and compare the results of the simulation to corresponding real-world evacuation times. Moreover, we anticipate the extension of the model with extra factors related to moving environments. For instance, the pedestrian module could potentially account for effects caused by the loss of postural stability in passengers – stumbling, falling and occurrence of collision-induced injuries. Though the simulator already generates satisfying results in cases with the moderate movements of the platform, we assume that in the extreme settings (maritime accidents, earthquakes, storms etc.) we could hardly achieve the same level of realism without accounting for the motion-induced interruptions, loss of balance or consciousness.

As for the platform motion model, its further development suggests the implementation of the degrees of freedom that have been left outside the scope of this paper as well as individual centers of rotation for each of them. Through the listed improvements, we are looking forward to achieving the ultimate goal – the development of a versatile yet robust model of walking behavior on an arbitrarily moving platform.

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