Microscopic Simulation of Evacuation Processes on Passenger Ships

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Abstract. The analysis of evacuation processes on-board passenger ships has attracted increasing interest over the last years. Most of the approaches utilise so called flow models. Cellular automaton models, widely used for traffic simulations, on the other hand provide a more natural approach towards pedestrian dynamics. Two major difficulties are intrinsical to the problem: two-dimensional movement of pedestrians and the complexity of psychological and social influences. In this paper a simple CA-model for the description of crowd motion is presented and its implementation in a simulation software outlined. The validity of the assumptions and the scope of the applications will have to be scrutinised by comparison with empirical data from actual evacuations or drills.

1 Safety of Passengers On-board Ships

The safety of passengers on-board ships is a central topic in the design and operation of passenger ships [1,2]. Due to the special circumstances on-board a ship, a careful consideration of problem areas and potential hazards is necessary [3,4].

1. Depending on the area of operation it is usually not possible to provide additional support in terms of men or material above those that are available on-board within a short time span.
2. In case of a major incident where the ship has to be abandoned there is an unalterable upper limit for the available evacuation time given by the stability of the ship.
3. The connection between the design and operation of a ship and its safety is very close. Therefore, shortcomings stemming from the design are hard to counterbalance afterwards.

Passenger ships differ in many respects: The area of operation, the number of passengers, the speed, the profile of the passengers (age, time of stay, etc.). An illustrative example are the differences between fast ferries and cruise ships, where the journey usually lasts a few hours for the former or days for the latter and that are operated close to the shore or on the high sea.

In any case, it is essentially important to assess and validate the safety of a certain design and operational procedure. There are two main aspects that have to be kept in mind: one is the overall evacuation time which is used as a benchmark and the second is the sequence of the evacuation. With regard to the latter the aim is the identification of potential bottlenecks and retardation. Applied at an early stage of design such an analysis will not only pursuit the validation of an existing design or evacuation plan but also their improvement. Special attention has to be paid to the various influences on the outcome of an evacuation illustrated in Fig. 1.

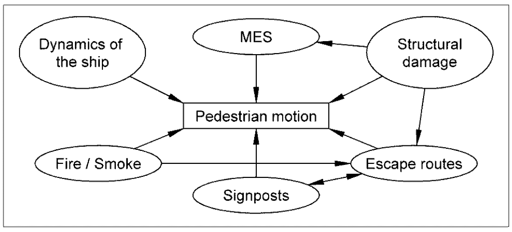

Fig. 1. The design and operation of a ship influence the movement of passengers on-board. The diagram shows the most important factors with regard to safety and evacuation. MES is short for Marine Evacuation System which comprises slides and life-rafts. This is understood to include lifeboats where they are part of the evacuation system.

The outline of the paper is as follows: The next section will give an overview of the different approaches to model pedestrian dynamics. In Section 3 we will present a cellular automaton model for pedestrian motion which provides the basis for the simulations presented in Section 4. Finally, we will summarise the results and give a conclusion regarding future developments.

2 Different Approaches to Pedestrian Dynamics

Pedestrian traffic can be modelled on different temporal and spatial scales (for an overview cf. [5,6] and references therein). In principal, there are two different approaches for the mathematical modelling of pedestrian flows, namely the microscopic and macroscopic. Macroscopic models are based on the similarities of pedestrian flows with liquids or gases [7–9]. The basis of such a model is the continuity equation which has to be supplemented by data about the relation of density and flow. The analysis of empirical data has revealed that the velocity distribution of pedestrians is nearly Gaussian [10,11]. Such empirical data are used to calibrate the parameters, like the viscosity or the Reynolds number. Unfortunately, these parameters are hard to identify in real world systems.

In microscopic models the pedestrians are identified as basic entities [12]. On contrary to macroscopic models the movement of single persons is modelled. Although this increases the computational effort, it allows to take into consideration individual behaviour. Every person is described by a set of parameters, e.g., age, sex, or walking speed. For a realistic simulation these are drawn from distributions.

One example for a microscopic model is the social force model by Helbing [5]. The influences of the physical and social environment are described by a social field, which is continuous in space. In some microscopic models the space is subdivided into cells of a certain size, which are either occupied by one or several persons [13–16]. In the next section we will describe a first cellular automaton approach based on few first principles.

For complex practical applications one can think of combinations of both approaches, either in the sense that the scale lies in between a description of single persons on the one and completely neglecting individuality on the other hand. Furthermore, a combination of fluid-dynamic and microscopic models in a semi-phenomenological way is possible: Some parts of the system are described by cellular automata, the connection is made via a phenomenological hydrodynamic model.

3 A Cellular Automaton Model for Crowd Motion

Cellular automata are widely used in traffic simulation. For an overview cf. [17–20]. They are, however, basically one-dimensional. A road is divided into lanes and the direction of the moving cars is fixed. A similar approach for pedestrian movement where overtaking or passing is introduced via lane-changing can be found in [16]. Pedestrian motion is usually different: the movement is truly two-dimensional, acceleration occurs instantly and change of the direction is possible and takes only a very short time. Nevertheless, several cellular automata have been developed for pedestrian dynamics [13,14,16]. The connection between the individual parameters and the crowd flow made in a simulation by an algorithm based on the motion of single persons is shown in Fig. 2.

The basic principles of the cellular automaton model for pedestrian flow described in this paper are the following [21]:

1. The floor plan is divided into quadratic cells. The length of one side is 0.4 m (cf. Fig. 3).
2. Each cell can either be empty or occupied by only one person.
3. Individual persons may differ in their characteristics or abilities. This is reflected by a set of parameters. The values of those parameters vary individually.
4. The motion of the people is described by their direction and walking speed and obeys universal laws that hold for everyone.

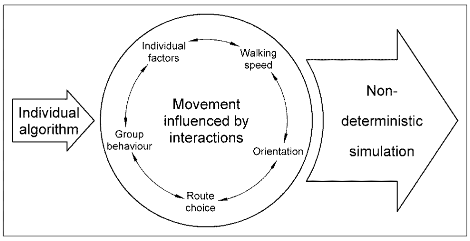

Fig. 2. The algorithm models the evacuation sequence on the level of individual persons interacting with each other. Due to the stochastic factors the result is non-deterministic, e.g., a statistical distribution for evacuation time, etc.

5. Walking speed and direction might be altered non-deterministically with certain probabilities. This accounts for various psychological and social factors not directly represented in the model.

The walking speed is at most 5 cells/second corresponding to 2 m/s where every person has an individual upper limit $v^i_{\rm max}$ due to his or her physical abilities. For the actual speed it holds $v^i \leq v^i_{\rm max}$.

Once the floor plan is discretised and the initial distribution of the passengers entered, the positions are updated sequentially, where the current person is chosen at random. It is desired to choose the direction along the shortest escape route and maximise the walking speed $v^i \to v^i_{\rm max}$. The route choice is supported by looking ahead as far as possible; the maximal distance covered is limited by an individual parameter $d^i_{\rm sight}$, however; walls, bendings, and other people reduce the sight. If the destination cell is occupied then alternative cells are chosen, first by varying the direction then by reducing the walking speed. If forward motion is not possible the person comes to a halt. This might cause "deadlock" situations that are resolved after a certain number of time-steps. If a person has not moved at all longer than $t^i_{\rm dl}$ she or he turns around.

There is a random probability $p^i_{\rm dir}$ for swaying (e.g., abruptly changing the direction) and indecision $p^i_{\rm vel}$ (e.g., stopping). Both are random numbers between zero and one drawn from a uniform distribution. This is to account for further influences that have not been included yet, like psychological factors or the dynamics of the ship.

Once the destination cell is determined $(x_{\rm dest}, y_{\rm dest})$ the person tries to move directly towards this cell swerving other persons and obstacles. The algorithm is schematically presented in Table 1.

In our approach we have utilised a random sequential update, whereas a parallel update is commonly used in cellular automaton models and in many cases it is crucial for their validity and success. On the other hand in the situation described here, where the update does not represent the movement of bacteria or ants, but rather the dynamics of human beings which is more

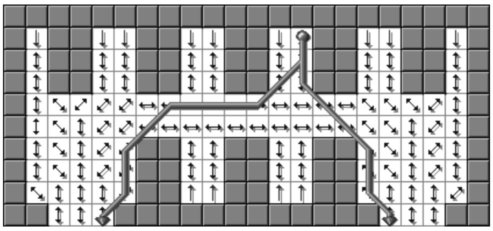

Fig. 3. Schematic view of a number of cabins facing a corridor. The floor plan is divided into quadratic cells where the length of one side is 0.4 m. Information about possible walking directions is given by the small arrows that represent signposts or panic bars. Possible routes emerging through orientation along the signposts are shown by the thicker long arrows.

complex on the individual scale a sequential update might be tolerable or even better than a parallel update. One might also think of an additional individual parameter like the ability to assert oneself that would make a parallel updating scheme superfluous. As long as those topics are neither investigated by simulation nor by comparison to empirical data it would be premature to give a decisive statement.

4 Simulating Evacuation Processes for Passenger Ships

The investigation and simulation of evacuation processes has originally been applied to buildings [15,22–24] or in the the aviation industry [25]. Recently, however, the methodology has also been transfered to ship evacuation, taking into account the special circumstances outlined in Section 1 [3,4,26,27].

Hitherto, escape routes on ships have been planned according to non-performance based rules stated in the regulations for "Safety of Live at Sea" (SOLAS) [1,28] formulated by the International Maritime Organisation (IMO). The width of doors and hallways was determined by simple empirical formulas to ascertain a minimal flow of persons. Interactions that occur in crowd motion have been accounted for – if at all – by factors in these formulas. On the way towards a performance based methodology, e.g. assessing the evacuation sequence and time, a first step has been to introduce preliminary guidelines based on a hydrodynamic model [2].

The next logical step is to go towards a method that is based on single persons as the smallest entities to take into account individual differences. Bottlenecks will be identified during the simulation and it is possible to calculate the overall evacuation time based on the interaction of individuals, which causes the complex phenomena observed in passenger flow and evacuations. Moreover, it shows how many people will come to each assembly station and where improvements in the architecture of the ship are possible.

```
for i := 1 to NumberOfPersons step 1 do
                                  The array of persons is assumed to have been shuffled.
    Indecision := rand();
    Sway := rand();
    ...                          Scan fields ahead (at most d^i_sight) following the signposts
    → sight, destination (x_dest, y_dest)
                                                                        sight ≤ n^i_sight
    v = max(v^i_max, sight/4);
    if (Indecision ≤ p^i_vel) then v = 0; fi
    dir = (y_dest − y_curr, x_dest − x_curr);          only discrete values in steps of 45°
    if counter^i > t^i_dl then dir+ = 180°; fi                            resolve deadlock
    if (Sway >= p^i_dir) then dir = ±45°; fi                    with random probability
    for j := 0 to v − 1 step 1 do
        if (destination cell free) then move;
                                   else dir ± 45°           with random probability;
                                        if (destination cell free) then move;
                                                                  else v = 0;
                                                                       counter^i + +;
                                        fi
        fi
    od
    if (current position on rescue cell)
      then take personi out; fi
od
```

Table 1. Outline of the CA-transition function. This is the loop over all persons done in one time step (assumed to be one second in reality). It will be repeated until all persons have reached the rescue cells.

The advantages of a simulation are clear: In contrast to a incomprehensible formal calculation, where only the output does have a well-defined meaning, the sequence of an evacuation is visualised.

Above the parameters v^i_{max}, p^i_{dir}, p^i_{vel}, t^i_{dl}, and n^i_{sight} that pertain to the individual person, there are two parameters that are mainly determined by the evacuation system: the time to deploy the evacuation system t_{deploy} and the time it takes one person to embark t^i_{embark}. Finally, the reaction time t^i_{react} is a mixture since it comprises both, personal and external influences. It may include the time it takes to detect a fire and trigger the alarm as well as the individual reaction time. The former can be represented by a general offset. However, this will just increase the overall evacuation time and can be added afterwards. For a single person the time to leave the ship or dangerous area is $T^i = \max(t_{\text{deploy}}, t^i_{\text{move}} + t^i_{\text{react}}) + t^i_{\text{embark}})$, where t^i_{move} is calculated as outlined in Table 1. The overall evacuation time is then $T = \max_i T^i$.

The comparison of a simulation with evacuation drills bears a number of difficulties, though. On the other hand, the advantages of a simulation stem from the same reasons as the problems. Evacuation drills are carried out under ideal conditions: The ship lies in the harbour, the people are instructed and told not to hurry and take care not to get injured. There is of course no fire or structural damage. If a simulation, however, is able to reproduce or predict the outcome, e.g. evacuation time or retardation areas, of a drill, it can be used to include aggravating circumstances like heel or trim, fire or structural damage or the insufficient orientation or non-optimal behaviour of passengers due to stress.

Every fast ferry or High Speed Craft undergoes a practical evacuation drill. To save costs and reduce the effort, usually one half of the ship is used carrying half or less of the maximal passenger load.

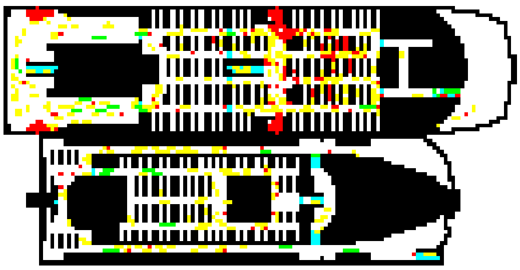

Fig. 4. A sample output of simulation of a high speed craft: Walls and inaccessible areas are drawn black. Persons are represented by coloured dots (shown in greyscale here), dark grey means zero and light grey maximal velocity. Initially all the people are in the right half, the exit is at the left, on the lower deck, shown in the upper part of the picture.

For the test of the high speed craft that has been investigated in our simulation (the floor plan is shown in Fig. 4) there have been 100 persons on-board the ship that is build to carry a total of 450 persons. The escape route for both the test and the simulation was chosen to be the worst case namely passengers starting in the front and embarking via the evacuation system in the rear. Figure 4 shows a sample output of the simulation at one time step.

The parameters are chosen from uniform distributions: 2 cells/s $\leq v^i_{\text{max}} \leq$ 5 cells/s, 10 s $\leq t^i_{\text{dl}} \leq$ 40 s, 10 cells $\leq d^i_{\text{sight}} \leq$ 100 cells, 0 s $\leq t^i_{\text{react}} \leq$ 10 s, $0 \leq p^i_{\text{vel}} \leq 0.3$, and $0 \leq p^i_{\text{dir}} \leq 0.01$. t^i_{embark} was set to 5 s for all persons and t_{deploy} to 300 s (5 minutes).

After 100 simulation runs the mean value of the evacuation time was close to that gained in the test. For example, in the simulation the first person reached the embarkation station after 20 to 30 seconds, in reality after 24 seconds. The overall evacuation time of 14 minutes in the test lies within the range determined in the simulation. The bottleneck is the time to deploy the

MES which caused jams in front of the exits. This comparison of evacuation drills with simulation results will be used in future to collect more data and calibrate the model.

The evacuation plans for ships that are already built can profit by a simulation, too. If there are any bottlenecks they can be mitigated by an appropriate behaviour of the crew and the adaption of the evacuation procedure. And the software might be used for training purposes. The clear visualisation can provide a way to understand phenomena like crowd motion and the influence of subtle changes or differences in the geometry or evacuation procedure.

5 Summary and Conclusion

We have introduced a microscopic model for pedestrian dynamics. Based on this cellular automaton, simulations of ship evacuations have been carried out. It is possible to reproduce the results of evacuation drills that take place under ideal conditions if the parameters are chosen appropriately. Scenarios that cannot be accessed via evacuation tests — including increased stress, heel or trim, fire and structural damage — can be simulated. Therefore a computer simulation is a fast and cost-effective tool to assess and increase ship safety at both design and operational phase. However, the desired standards in terms of acceptable evacuation times in different scenarios have to be set by the authorities and the shipping industry.

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