



Eidgenössische Technische Hochschule Zürich  
Swiss Federal Institute of Technology Zurich

# Lecture with Computer Exercises: Modelling and Simulating Social Systems with MATLAB

Project Report

## **Modeling of a passenger ship evacuation**

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Zurich  
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## **Agreement for free-download**

We hereby agree to make our source code for this project freely available for download from the web pages of the SOMS chair. Furthermore, we assure that all source code is written by ourselves and is not violating any copyright restrictions.

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Modeling of a ship evacuation

is original work which I alone have authored and which is written in my own words.\*

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## 1 Abstract

The evacuation of a passenger liner is problematic due to a big mass of passengers wanting to reach the rescue boats. Real data can just be gained on accidents. Another way is to simulate such scenarios using computer models. Our approach was to take a common ship shape with real floor plans and run simulations on it with a continuous space social force model as introduced by Helbling et al [1]. A implementation of this has already been done by a former MSSSM group [2] on building structures. We took this C based code with a MATLAB interface and changed it to our needs.

Several scenarios were simulated. As a standard we took a simplified floor plan of the passenger liner Costa Serena, a 290 meter long ship with up to more than 4000 passengers. We compared it to modifications in the stair placement as well as rescue boat capacity adjustments. Another idea was to implement the leading and controlling influence of staff on the passengers.

Our simulations clarified that there is a potential to decrease the overall evacuation time. The most weightily influence had the stair displacement with up to 20% faster evacuation. on the other hand, the crew influence model seemed to be to simplified. We did not see a lot of improvement in this scenario. However, a more detailed model would probably lead to better results.

In a future work one could merge our modifications to get an even safer evacuation. The potential exists.

## 2 Individual contributions

The whole project was completed as a team. For sure we took into consideration all the personal backgrounds and knowledge. That is the reason why Raphael and Manuela focused on implementing the computer code. Whereas Andreas and Fabian concentrated on providing background information, compared the results with the reality and doing its verification. A more detailed breakdown can be seen by looking at the GitHub time line of our project.

## **3 Introduction and Motivations**

### **3.1 Introduction**

The evacuation of a passenger liner due to fire, sinking or other issues leads to several problems. A large amount of passengers try to save their lives and get to a rescue boat. Narrow and branched floors, smoke, inflowing water, the absence of illumination, rude passengers and so forth can make the evacuation difficult and reduce the number of survivors. There are a lot of norms how to minimize the harm of such an evacuation. For example there are rules on the number of rescue boats dependent on the amount of passengers [3]. With dry runs the staff is prepared for the case of emergency et cetera. In real life ship corridor reproductions, the behavior of distressed people is studied. Another approach is to model such ship evacuations numerically on the computer. As an example the software maritimeEXODUS by a development team from the University of Greenwich is a computer based evacuation and pedestrian dynamics model that is capable of simulating individual people, behavior and vessel details. The model includes aspects of people-people, people-structure and people-environment interaction. It is capable of simulating thousands of people in very large ship geometries and can incorporate interaction with fire hazard data such as smoke, heat, toxic gases and angle of heel [6]. Our approach is similarly to model a passenger ship with a common geometrical outline and ground view. In an optimization process we will thereafter look for an ideal ground view, rescue boat distribution and their size to minimize the time needed for evacuation. Finally we will make a statement on possible improvements.

### **3.2 Motivation**

Even though modern ocean liners are considered to be safe, the latest occasions attested that there is still potential for evacuation and safety improvements [7]. Certainly we know that this science is very advanced and practiced since the sinking of the Titanic. Nevertheless knowing that there are still bottlenecks on the ships we are very motivated to detect and eliminate them with our mathematical models.

### **3.3 Fundamental Questions**

To find these bottlenecks we run a mathematical model of a ship structure with several decks and its passengers [5]. After we localized these places we are interested in the answers of the following questions:

How much time can be saved by varying the dependent variables mentioned below:

- How much people can be saved by changing the disposition of the specific room types?
- Where are the bottlenecks during the evacuation? How can they be avoided?

What is the influence of the rescue boats?

- Are small or bigger boats better?
- Where do they have to be positioned?

We analyze the difference between uncontrolled and controlled passenger flow:

- Is the crew able to prevent chaos in the evacuation process?
- What is the best way to lead the passengers out of the ship?

In addition we are keen to know if our model is a good abstraction of the reality.

### 3.4 Expected Results

Before making computer simulations we discussed, what we expect as results out of the simulation:

- Even though modern ships are quite optimized in regard to evacuation time, they are always a compromise between safety and luxury. Therefore we are convinced to find a superior adjustment of the decks geometries to increase the survival rate.
- Since the rescue boats can not be averaged but are rather concentrated over one or two decks, we consider the staircases as the bottlenecks.
- In aligning this variables we are persuaded of a reduction of the overall evacuation time.
- We suppose that smaller and evenly spread rescue boats combined with a higher quantity will scale the evacuation time down. Certainly there is going to be an optimum in size which we are willing to find.
- By controlling the rescue we assume to detect a huge decrease in evacuation time. Further we have the hypothesis that disorder can be minimized. The crew who is familiar with the decks and the emergency exits is able to guide the passengers in minimum time to the rescue boats.

- There are many parameters we do not model in our simulation. For example fire and smoke, the tilt of the ship or handicapped and petrified passengers are disregarded. By leaving out this details we get a very simplified model. However, by starting the optimization process by data of a nowadays passenger liner we hope to see some real evacuation dynamics in this system and therefore make conclusion on the fundamental questions.

## 4 Description of the model

We base our model on the work done by a group of former MSSSM students, by name Hans Hardmeier, Andrin Jenal, Beat Kueng and Felix Thaler [2]. In their work "Modeling Situations of Evacuation in a Multi-level Building" they wrote a computer program in in the language C with a MATLAB interface to rapidly simulate the evacuation of multi-level buildings.

### 4.1 Social force model

Our approach is the social force model described by Helbling, Farkas and Vicsek [1], as summarised below. In order to observe an escape panic situation and especially bottlenecks, they built up a continuous-space model. In mathematical terms they took Newtons second law and introduced a mix of socio psychological and physical forces for each so called pedestrian.

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i f_D + \sum_{j(\neq i)} f_{ij} + \sum_W f_{iW} \quad (1)$$

Each pedestrian has his own mass and a direction  $e_i^0$  in which he wants to move with a certain velocity  $v_i^0$ . He tries to adapt his own velocity to the wanted velocity with a given characteristic time  $\tau_i$ .

$$f_D = \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} \quad (2)$$

There are additionally interaction forces  $f_{ij}$  between the pedestrian and other people including an exponential part for the tendency of two pedestrians to stay away from each other. The second and third term are zero if the two pedestrians are not in touch. Elsewise there is a force in tangential direction  $t$  and in radial direction away from each other.

$$f_{ij} = \{A_i \exp[(r_{ij} - d_{ij})/B_i] + kg(r_{ij} - d_{ij})\} \mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij}) \Delta v_{ji}^t \mathbf{t}_{ij} \quad (3)$$

To be able to handle with walls there is another forces  $f_{iW}$  introduced. Its direction is away from the surrounding walls and the structure is similar to the one for the interaction between pedestrians.

$$f_{iW} = \{A_i \exp[(r_i - d_{iW})/B_i] + kg(r_i - d_{iW})\} \mathbf{n}_{iW} - \kappa g(r_i - d_{iW})(\mathbf{v}_i \cdot \mathbf{t}_{iW}) \mathbf{t}_{iW} \quad (4)$$

## 4.2 Ship structure

To apply the force model on a realistic situation a ship has to be implemented as well. Floor plans from the Costa Serena were taken [5]. In order to make strong conclusions we want to keep the following variables independent:

- Number of passengers (4400 agents)
- Overall capacity of the rescue boats (4680 seats)
- Ship size (290 meters long) and outer shape

In order to optimize the evacuation time, we change the following dependent variables:

- Stairs and their positions
- Rescue boat size, number and position
- Control of the passenger flow by crew members (e.g. is there staff to lead the passengers and how are they doing it?)

## 5 Implementation

As mentioned above our code is based on the work of a previous project. Working on a different problem statement we had to make several adjustments and adapt it to our simulation model. In this chapter we will explain the most significant modifications we made. For the exact understanding of the original code and the process of optimization, please refer to the documentation of the previous project group [2], especially chapter five and nine or our code in the Appendix.

### 5.1 Basic code

The builders of the code we base on created a flexible model to simulate building structures. The floors can be feed as graphic data into the system where different colors stand for different areas. Black are walls, red stairs up, blue stairs down, green exits and purple agent spawning areas. The data is evaluated in MATLAB in matrices. Information on parameters such as timestep, simulation time, force characteristics et cetera can be read in using a config file which is evaluated on simulation start.

With a fast sweeping algorithm in C a vector field is created for every floor pointing in direction of the shortest way towards stairs and exits. In a loop over all passengers the acting forces on them are calculated and via forward Euler converted into velocities.

$$\mathbf{v}_{i,new} = \mathbf{v}_{i,previous} + \frac{\sum f}{m_i} dt \quad (5)$$

Again with the forward Euler scheme positions are calculated that were reached in a finite timestep.

$$\mathbf{r}_{i,new} = \mathbf{r}_{i,previous} + \mathbf{v}_{i,new} dt \quad (6)$$

### 5.2 Code adjustments

This subsection is intended to illustrate the modifications in the code. We explain the difference between our model and the one used in [2] and the reason why a modification was necessary. Further we define the assumptions we made to minimize the modifications. Finally we specify the modifications and where they take place. Those parts are however not essential for the results of our research. They are meant to be an assistance for following projects.

### 5.2.1 Exits

#### Reason:

The first change which was necessary was due to the fact that the exits in our simulation are not simply on the lowest floor.

#### Assumption:

In case of an emergency all agents are keen to leave the ship as fast as possible. Therefore in our simulation all passengers above the exits floor are only enabled to move down and passengers lower than the exit floor move upstairs.

#### Function:

*applyForcesAndMove.m*

#### New variables:

To define the floor in which the exits are we introduced a new variable *floor\_exit* in the config file.

#### Modifications:

Since we defined our exit, we are able to easily modify the code by splitting the loop, in which the force-calculation and the movement of the agents take place, in two parts. First we loop over all floors higher than the exit floor. In those the agents are only allowed to move down. Secondly we do the same for all people in the floors lower than the exit floor where the passengers only can move up. The only floor left is the exit floor where the agents only move towards exits.

Because of this modification it is not necessary to loop twice over all floors. Consequently our code remains fast and efficient. We also kept the simple concept of vectors out of booleans. This means for each agent there is one number set:

- If the agent reaches a staircase and therefore changes the floor 1 is stored in the logical array *floorchange*
- otherwise a 0 is stored

The assumption is also a very helpful simplification for the pictures since we do not have to mess with the problem of stairs overlapping.

### 5.2.2 Different exits

#### Reason:

In our model the exits are the rescue boats, which can only hold a limited number of agents. Therefore we had to find a way how to differ the exits from each other and to assign a specific number to every exit. This number defines how many agents can stay on that rescueboat.

#### Function:

*loadConfig.m*

**New variables:**

- *exit\_count*, to define the number of exits.
- For each exit  $k$  a variable *exit\_k\_nr*, to define the number of agents it can hold.
- To store how many agents can exit in one specific exit, we introduced a matrix *exit\_nr matrix*, where the number of agents that can exit is indicated for each pixel.

**Modifications:**

Some changes in the decoding of the pictures were necessary. The aim was to change as little as possible to the original code. It was clear that we are going to need as many different colors as we have different exits, to be able to distinguish them during the simulation.

We define every pixel which has red to value=0, blue value=0 and green value unequal to zero a "exit-pixel". Now we can specify a lot of different colored exits by using green values between 256 and 256-*exit\_count*.

We implemented the matrix *exit\_nr* similar to the already existing one *img\_exit*, in which we store a count to number the different exits. The number is defined by the green value of the pixel that belongs to this exit.

```
%make a zeros matrix as big as img_exit
config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));
% build the exit_nr matrix
config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0 & img_build(:, :, 2) ==
(256-e) & img_build(:, :, 3) == 0 ) ;
```

Figure 1: Implementation of the exit\_nr matrix

### 5.2.3 Closing exits during simulation

**Reason:**

To close an exit as soon as it let a specific number of agents in, we have to keep track of the number of agents that already used this exit.

**Function:**

*loadConfig.m* and *applyForcesAndMove.m*

**New variables:**

*exit\_left*

**Modifications:**

For this purpose, we defined the matrix *exit\_left*, in which we store the number of agents who can exit for every exit.

```
%make a zeros vector as long as exit_count
config.exit_left = zeros(1,config.exit_count);
%loop over all exits
for e=1:config.exit_count
%build the exit_nr matrix
config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0 & img_build(:, :, 2) ==
(256-e) & img_build(:, :, 3) == 0 );
%build the exit_left matrix and save the number of agents the exit can hold
config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));
end
```

Figure 2: Implementation of the exit\_left matrix

In the loop where the forces and velocities are updated, (*applyForcesandMove.m*) we added a piece of code, which updates the exit\_left matrix at every timestep. First, we get the number of the current exit.

```
%save current exit nr
data.current_exit = data.exit_nr(round(newp(1)), round(newp(2)));
```

Figure 3: Implementation to get the current exit number

Then we update the *exit\_left* matrix by counting down the number of agents allowed to exit by 1. If the allowed number of agents exited the number is 0. Now we have

```
%update exit_left
data.exit_left(1,data.current_exit) = data.exit_left(1,data.exit_nr(round(newp(1)),
round(newp(2)))) - 1;
```

Figure 4: Implementation to update the exit\_left

to close the current exit, by changing it into a wall. Therefore we have to update the *img\_wall* matrix.

```
%close exit if there is no more free space
if data.exit_left(1,data.current_exit) < 1
%change current exit to wall
data.floor(data.floor_exit).img_wall = data.floor(data.floor_exit).img_wall == 1 ...
— (data.exit_nr == (data.current_exit));
data.floor(data.floor_exit).img_exit = data.floor(data.floor_exit).img_exit == 1 ...
& (data.exit_nr = (data.current_exit));
```

Figure 5: Implementation to close filled boats

### 5.3 Crew command simulation

**Reason:**

In reality an evacuation is coordinated. Loudspeaker announcements and crew members lead the people to the exit floor. In some cases there are even assembly points on the deck where people meet. Afterward they go with crew members to the rescue boats. In our first simulations we saw, that the last passengers escaping the ship have to walk all the way along the ship to get into a rescue boat in the middle of the deck. Those boats are the only ones that are not fully loaded at this time. To counteract, we tried to implement somehow the interaction of the passengers and the crew members.

**Assumption:**

In order not to change too much the structure of our standard evacuation code, we tried to implement the scenario in two steps. First just some rescue boats in the middle of the ship are available what can be interpreted as a crew leading people to those boats because they know that the boats near to the stairs should be left unalloyed for the last passengers to be evacuated rapidly. In a second step, all rescue boats are opened when a certain number of passengers already left the ship.

**Function:**

The whole basic code has been copied and adjusted in several positions, mainly in loadConfig.m and applyForcesAndMove.m.

### 5.4 Video creation

**Reason:**

In the basic code there was a graphical output into eps-formated files possible on every timestep. The images then had to be converted into a video file in a postprocessing part. This is not an optimal implementation for a fast system. Furthermore

it turned out that we could increase the simulation speed by factor two just by saving not on every single timestep but only on every 10<sup>th</sup> or 100<sup>th</sup>. Another issue was the conversion from eps to a video file. To simplify the handling, we used a MATLAB function to create directly a video out of the figures instead of making a detour via images.

**Function:**

*simulate.m, initialize.m*

**New variables:**

*save\_frame*

## 5.5 System output

**Reason:**

Storing the simulation output is important to be able to analyze and optimize the system. The output of the basic code was just a plot with agents left the building over time and the above mentioned graphical output of the floor plans over time. We extended the output and created a dump struct where all the important variables are listed over time. That struct is the system output at simulation end and it can be used in a postprocessing part to generate meaningful graphs and data.

**Function:**

*simulate.m*

**New variables:**

*output*

## 5.6 Postprocessing

**Reason:**

To analyze the gathered data in a systematic way and to create consistent plots we created a postprocessing file. The output file can be loaded in MATLAB using the load command and is thereafter automatically evaluated. Plots with agents per floor over time, left space in rescue boats over time and agents that left the ship over time are created with proper axis label and so on. Additionally there is an output in the MATLAB command window with timestep, number of steps, total simulation time, agents on ship on start, agents on ship on simulation end, agents deleted due to Not-a-Number-positions and the characteristic  $t_{10}$ ,  $t_{50}$ ,  $t_{90}$  and  $t_{95}$  times.

**Function:**

*postprocessing.m*

**New variables:**

none of relevance

**Modification:**

We created the whole script ourself. It can be found in the annex.

## 5.7 Parameter input and config file

The social force model can be adjusted using different parameters e.g. to weight the importance of different forces among each other or to define the decay rate of these forces over the distance. Also the mass and radii of the passengers as well as their maximum velocity can be set. The parameters are written down in the config files that are passed to the MATLAB interface on simulation start. For sake of simplicity we adopted the force model parameters from the previous group. The parameters concerning the ship shape were adjusted so that they represent reality as far as possible.

In the annex a typical simulation input of the config file and some explanations can be found.

## 5.8 Ship Decks

The Costa Concordia has 14 decks which are all different from each other. They are connected by stairs and elevators in different configurations and they fulfil different purposes. There are decks for entertainment, eating, shopping, sports and so on. Due to the big differences of each deck, it is enormous time consuming to implement all these decks with all details in a model. So it is necessary to simplify the decks in a reasonable manner. Further the picture source is not perfect in size and data type so there is a manual conversion needed. In this chapter it is shown what assumptions were made and with which conversion techniques the decks were implemented into the model.

### 5.8.1 Conversion

First of all the decks have to match each other in pixel size and position to allow a flawless connection of the decks. So the size of some decks has to be adjusted and the stair overlay has to be matched as good as possible. Secondly doors, numbers, names and symbols are removed to have one connected surface without unreal obstacles.

Now that the surfaces are clean and connected, the colors have to be replaced by predefined colors of the code (purple for spawn of agents, black for walls, red for upstairs, blue for downstairs and different green type for each rescue boat).

In figures 6 and 7 a small portion of a deck with stairs, rooms, doors and elevators is

shown before and after conversion. In the converted picture is a blue block included for the stairs, which conversion will just be explained in the next part.

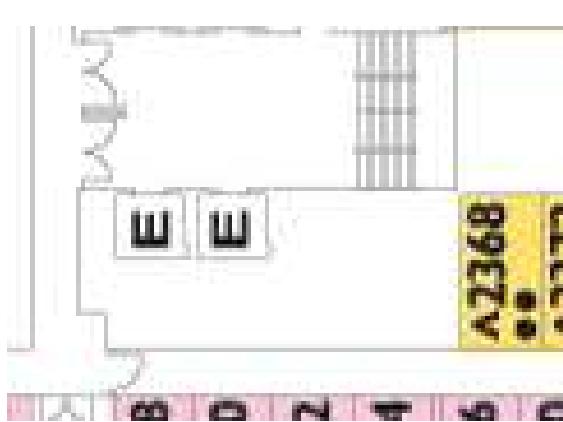


Figure 6: Deck before conversion

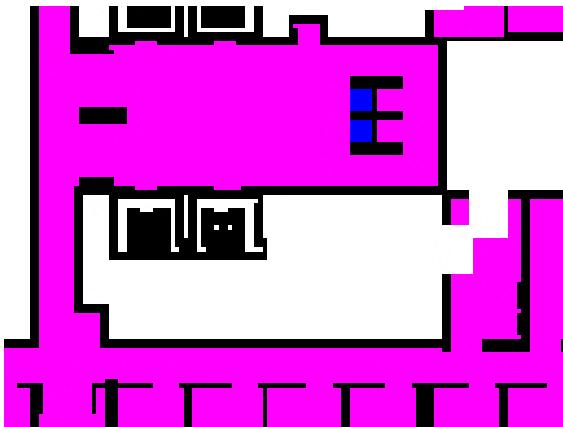


Figure 7: Deck after conversion

In most of the cases stairs from one to another floor are designed in a spiral way to minimize the consumed space. That leads to a problem by implementing the stairs into the model. It is not possible to make a clean transition from one floor to another without using some tricks.

There are special additional floors to overcome the mentioned problem in the work "Modeling Situations of Evacuation in a Multi-level Building" [2]. These additional floors which represents the stairs, are a fine method to create an infinite amount of floors and connections without any trouble. But it needs an additional floor for each connection.

While the agents on the ship march only in the direction of the rescue floor the connection can be simplified. So there is a new technique used to get rid of these additional floors.

In figure 8 a spiraling stairs connection between floor 01 and floor 02 is shown as example. The arrows in light blue are used to clarify the technique.

The agents arrive from the left on floor 11 and go into the direction of the arrow until they reach the blue box. There they are skipped down on the floor 10 and try to go to the blue box again. So they have to go around to be skipped down again on floor 09 and go around in the other direction. That continues until they reach floor 04 which is the floor with the rescue boats.

With that technique no additional floors are needed and we get very close to the real spiraling stairs. For the ship in that project this is sufficient, because the modeling fault will be in a lower degree than the one of other assumptions.

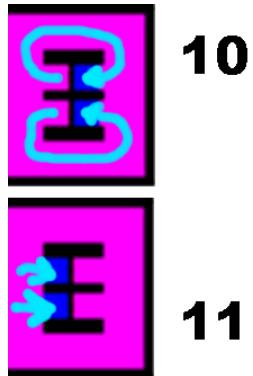


Figure 8: Stairs connection between floor 10 and floor 11

### 5.8.2 Similarities and reduction

The most important floor for the simulation is of course floor 04 because it holds all the rescue boats as seen in figure 10. There all agents have to pass and it is reasonable to have it very detailed. Floor 05 and 03 are the ones just above and beyond and will also have a non negligible influence on the agents movement.

The further we move the less important the deck configuration gets, because it is assumed that the stairs will be the bottlenecks. As long as the stair setup corresponds good to reality, the further decks can differ more. So we decided to convert deck 02, 03, 04 and 05 in detail and make a copy with adjusted stairs for each other floor. Floor 02 is used for the copy because it gets the closest to floor 01, 06 and 07 and is by that still a good approximation.

Floor 08 until 14 differ more from floor 02 but as long as they are far away from floor 04 it will not have a big influence. These last floors are also smaller than floor 02 and therefore the amount of floors is reduced to only 11 with approximately the same area as the original 14 floors.

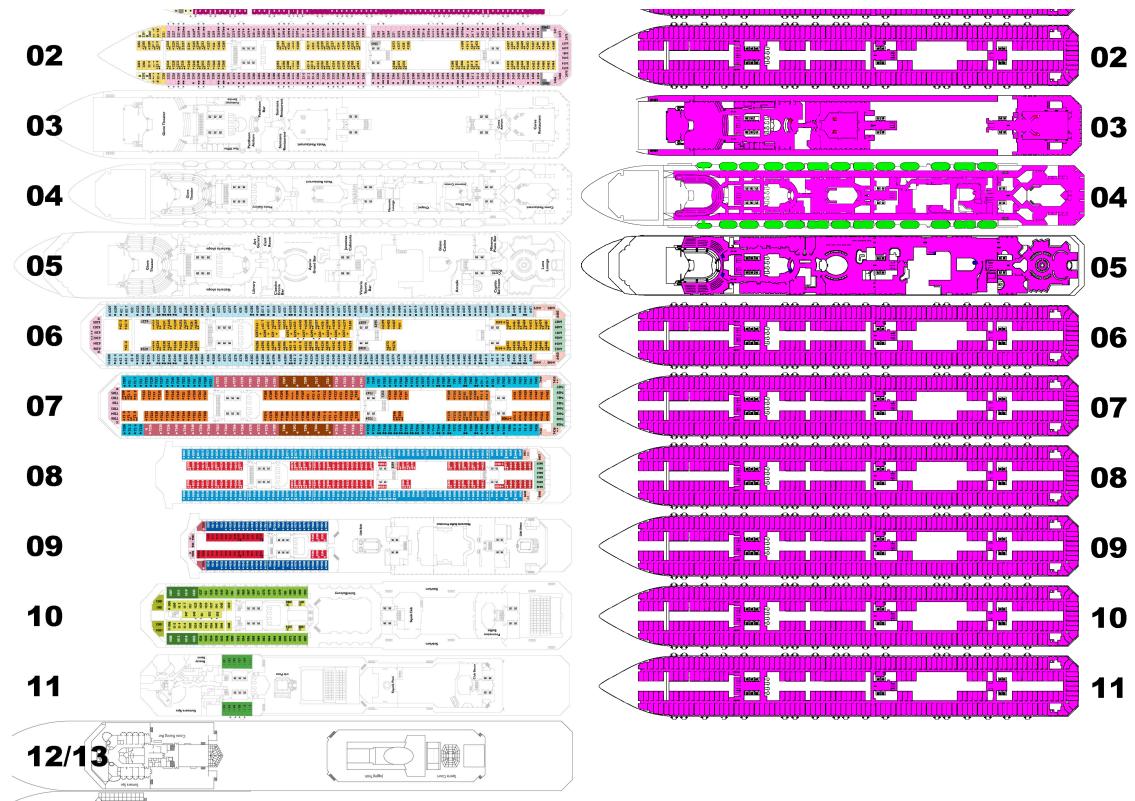


Figure 9: Original decks before conversion

Figure 10: Deck approximated and converted

## 6 Results and Discussion

### 6.1 Simulation issues

Some agents always stuck in the walls near the stairways. Those agents did not reach the exits. This is why we could not get a  $t_{100}$  time but just saved about 98% of all passengers. The frequency of this issue was especially high in small areas and with a high total passenger amount. However, there was a trade off between realistic clogging in stairways and good ratio of rescued people out of all passengers. We decided not to decrease the number of passengers or expand the stairs because we did not want to eliminate the realistic clogging behavior which is important for the simulation.

### 6.2 Simulation Results

#### 6.2.1 Standard ship

As listed above we were interested in the time in which a certain percentage of all agents was evacuated:

percentage of agents	10%	50%	90%	95%
evacuation time run1	16s	69s	167s	214s
evacuation time run2	16s	69s	164s	238s
averaged evacuation time	16s	69s	166s	226s

Table 1: Standard simulation: Needed time to evacuate a certain percentage of all agents.

Further our standard ship simulation showed the following performance:

#### 6.2.2 Modified room disposition

As we expected the standard simulation revealed that hold-up problems occur because of the staircases. As the flow everywhere else was quite dynamic we abstained from adjusting the room disposition but instead we inserted an additional staircase. This simulation yielded the following results:

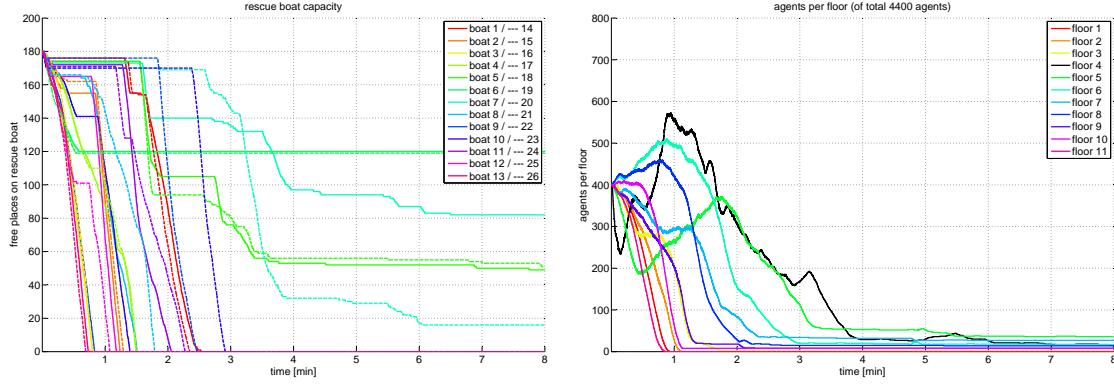


Figure 11: Standard simulation: Boat capacities during first simulation

Figure 12: Standard simulation: Number of agents per floor in first simulation

percentage of agents	10%	50%	90%	95%
evacuation time	16s	67s	145s	182s

Table 2: Added stairs simulation: Needed time to evacuate a certain percentage of all agents.

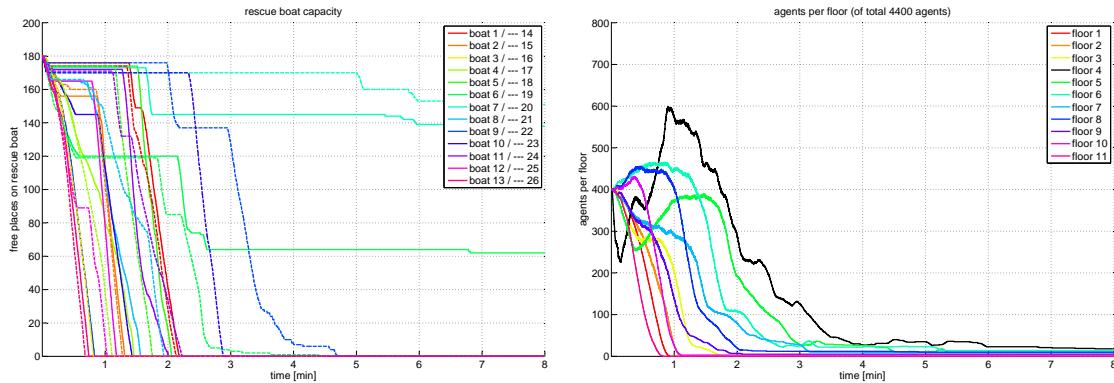


Figure 13: Added stairs simulation: Boat capacities during simulation

Figure 14: Added stairs simulation: Number of agents per floor

### 6.2.3 Modified rescueboat size

As we could see in the simulations with the standard ship, the rescue boats which are nearest to the stairs are filled first. This behavior is very intuitive. As soon as the nearest lifeboats are full, the agents continue to fill the other lifeboats. The greatest extension of the evacuation time occurs as follows: Towards the end of the simulation, not all lifeboats are still open. Therefore leftover agents, which walked in the direction of a lifeboat that closed in the meantime, have to cross a big distance to reach a lifeboat with free space.

We tried to avoid this delay by increasing the capacity of lifeboats near the stairs and removed some, which are the farthest away for the agents left over towards the end of the evacuation.

percentage of agents	10%	50%	90%	95%
evacuation time	17s	70s	154s	203s

Table 3: Varied boatsize simulation: Needed time to evacuate a certain percentage of all agents.

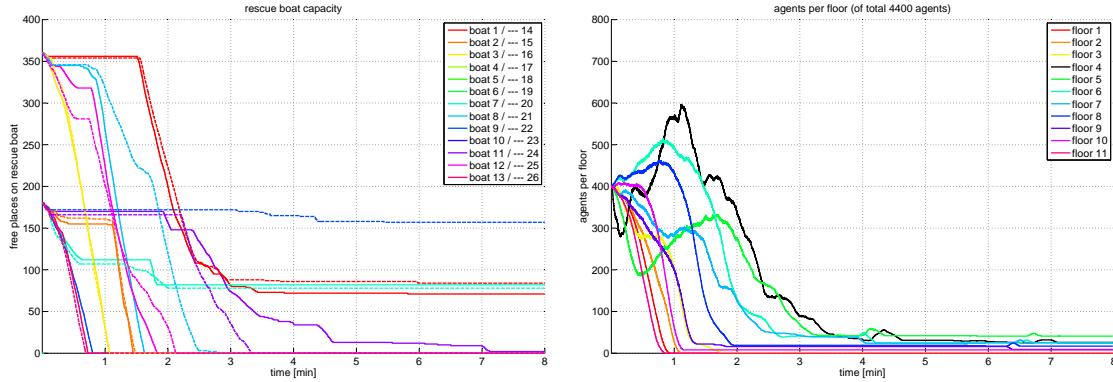


Figure 15: Varied boatsize simulation: Boat capacities during simulation

Figure 16: Varied boatsize simulation: Number of agents per floor

### 6.2.4 Crew command

As already mentioned in the implementation part, we changed our code in order to simulate staff controlling the rescue situation. The results of that extension can be

seen below.

percentage of agents	10%	50%	90%	95%
evacuation time	20s	78s	162s	219s

Table 4: Crew command implementation: Needed time to evacuate a certain percentage of all agents.

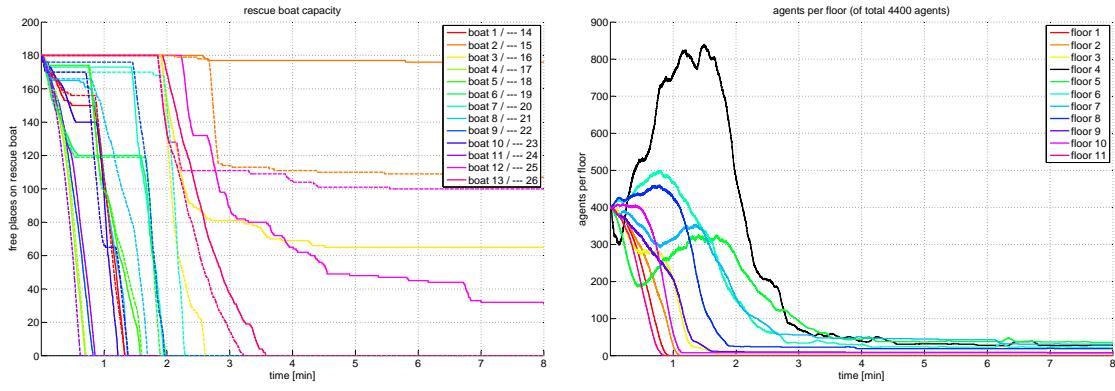


Figure 17: Crew command simulation: Boat capacities during simulation

Figure 18: Crew command simulation: Number of agents per floor

### 6.3 Comparison

#### 6.3.1 Standard - Modified room disposition

The Analysis of the simulation results showed that there is a huge potential in saving evacuation time. By adding just one additional staircase we were able to reduce the overall evacuation time by 42 seconds. Further 50% of all agents entered the exits approximately 2 seconds earlier compared to the standard model. In contrast to that the rescueboat capacity utilization remains basically the same.

#### 6.3.2 Standard - Modified rescueboat size

As the results above show, there is no significant acceleration in the first part of the evacuation achieved by changing the distribution of the lifeboats . But, there is clearly a difference in the second half of the evacuation. The last 5% of agents are

evacuated 23 seconds faster what is a huge speed up. This decrease in evacuation time is an effect of the reduced time the last agents need to leave the exit-deck.

### 6.3.3 Standard - Crew command

The results of the crew command extension are rather disappointing. On the one hand it was clear, that the first part of the simulation would become slower because the agents do not use the nearest boat. But on the other hand it was mentioned that the last part of the simulation has a significant speed up what is not the case. By looking at the video output the reason can be seen: The opening of the rescue boats near the stairs is useless at the point when only a few passengers are left because then they are already on the exit floor and walked towards the middle of the ship. However, the idea has not to be thrown away. An implementation with a continuous opening of the next outer boat when the midmost ones are filled would eliminate our problem and a faster total evacuation time could be reached.

## 6.4 General discussion

During our project we revealed a lot of adjustments which could make cruise ships safer. Definitely we are aware of the simplicity of our model. Nevertheless we achieved to decrease the evacuation time with our improvements as shown above. Further we were able to attest that the staircases are the bottlenecks and it is possible to save time by adapting the ship geometry. Due to lack of time and simulation problems we unfortunately did not manage to find the optimal rescueboat size. However we proved that there is a capability to save further time by varying its size and position.

## 7 Outlook

During our work, we found a lot of possibilities to improve the model. The target of an ongoing project could be to make the model more realistic. There are a lot of possibilities to achieve this goal.

Some suggestions:

- To take into account that not all people automatically know where exactly the nearest exit is, the initialization of the escape routes should be modified.
- In our model the agents are evenly distributed over the floors and decks at the beginning of the simulation. This is however a very unrealistic scenario. In reality the agents will be unevenly spread. The evacuation time would depend very much on the form of this distribution.

- Different scenarios like night, dinner-time etc. that would change the distribution of the agents significantly could be compared.
- In reality there are a lot of effects that could occur like fire, tilt of the ship, flooded areas, power failure, mass panic etc.

There are a lot of other interesting effects that could be looked at as well.

Some ideas:

- In the ideal case, the evacuations on a ship are planned well. A good idea would be to define specific control points at which agents gather first. From those points the agents would be led in small groups to the rescue boats by a crew member. It would be interesting to analyze the effect of such a efficient control.
- The optimal combination of the different modifications we analyzed in this project could be found and therefore a minimal evacuation time.

For sure further interesting outcomes could be made by simply merging our results, means for example varying rescueboat size and geometries.

## 8 References

### References

- [1] Helbling, Dirk et al (2000): Simulating dynamical features of escape panic.
- [2] Hardmeier,Jenal,Kueng,Thaler (2012): Modelling Situations of Evacuation in a Multi-level Building.
- [3] SOLAS (1974): International Convention for the Safety of Life at Sea. [http://www.imo.org/about/conventions/listofconventions/pages/international-convention-for-the-safety-of-life-at-sea-\(solas\),-1974.aspx](http://www.imo.org/about/conventions/listofconventions/pages/international-convention-for-the-safety-of-life-at-sea-(solas),-1974.aspx)
- [4] SHIP EVACUATION: <http://www.shipevacuation.com/>
- [5] CRUISE DECK PLANS PUBLIC SITE: <http://www.cruisedeckplans.com/DP/Main/decks.php?ship=CostaSerena>
- [6] University of Greenwich (2011): maritimeEXODUS. [http://fseg.gre.ac.uk/fire/marine\\_evac\\_model.html](http://fseg.gre.ac.uk/fire/marine_evac_model.html)
- [7] Havarie of Costa Concordia (2012): [http://de.wikipedia.org/wiki/Costa\\_Concordia#Havarie\\_2012](http://de.wikipedia.org/wiki/Costa_Concordia#Havarie_2012)

## 9 Appendix

### 9.1 Code

#### 9.1.1 *standard code*

```
1 function data = addAgentRepulsiveForce(data)
%ADDAGENTREPULSIVEFORCE Summary of this function goes here
3 % Detailed explanation goes here

5 % Obstruction effects in case of physical interaction

7 % get maximum agent distance for which we calculate force
r_max = data.r_influence;
9 tree = 0;

11 for fi = 1:data.floor_count
    pos = [arrayfun(@(a) a.p(1), data.floor(fi).agents);
13         arrayfun(@(a) a.p(2), data.floor(fi).agents)];

15     % update range tree of lower floor
    tree_lower = tree;
17
    agents_on_floor = length(data.floor(fi).agents);
19
    % init range tree of current floor
21    if agents_on_floor > 0
        tree = createRangeTree(pos);
23    end

25    for ai = 1:agents_on_floor
        pi = data.floor(fi).agents(ai).p;
27        vi = data.floor(fi).agents(ai).v;
        ri = data.floor(fi).agents(ai).r;

29        % use range tree to get the indices of all agents near agent ai
31        idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
                           pi(2) - r_max, pi(2) + r_max)';
33
            % loop over agents near agent ai
35            for aj = idx

37                % if force has not been calculated yet...
                if aj > ai
39                    pj = data.floor(fi).agents(aj).p;
                    vj = data.floor(fi).agents(aj).v;
41                    rj = data.floor(fi).agents(aj).r;

43                    % vector pointing from j to i
                    nij = (pi - pj) * data.meter_per_pixel;
```

```

45
47      % distance of agents
48      d = norm(nij);

49      % normalized vector pointing from j to i
50      nij = nij / d;
51      % tangential direction
52      tij = [-nij(2), nij(1)];
```

53

```

55      % sum of radii
56      rij = (ri + rj);

57      % repulsive interaction forces
58      if d < rij
59          T1 = data.k*(rij - d);
60          T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
61      else
62          T1 = 0;
63          T2 = 0;
64      end
```

65

```

66      F = (data.A * exp((rij - d)/data.B) + T1)*nij + T2;
```

67

```

68      data.floor(fi).agents(ai).f = ...
69          data.floor(fi).agents(ai).f + F;
70      data.floor(fi).agents(aj).f = ...
71          data.floor(fi).agents(aj).f - F;
```

72

```

73      end
74  end
```

75

```

76      % include agents on stairs!
77      if fi > 1
78          % use range tree to get the indices of all agents near agent ai
79          if ~isempty(data.floor(fi-1).agents)
80              idx = rangeQuery(tree_lower, pi(1) - r_max, ...
81                               pi(1) + r_max, pi(2) - r_max, pi(2) + r_max);
```

82

```

83          % if there are any agents...
84          if ~isempty(idx)
85              for aj = idx
86                  pj = data.floor(fi-1).agents(aj).p;
87                  if data.floor(fi-1).img_stairs_up(round(pj(1)),
88                                              round(pj(2)))
```

89

```

90                      vj = data.floor(fi-1).agents(aj).v;
91                      rj = data.floor(fi-1).agents(aj).r;
```

92

```

93                      % vector pointing from j to i
94                      nij = (pi - pj) * data.meter_per_pixel;
```

```

95          % distance of agents
96          d = norm(nij);

97          % normalized vector pointing from j to i
98          nij = nij / d;
99          % tangential direction
100         tij = [-nij(2), nij(1)];

101        % sum of radii
102         rij = (ri + rj);

103        % repulsive interaction forces
104         if d < rij
105             T1 = data.k*(rij - d);
106             T2 = data.kappa*(rij - d)*dot((vj -
107                                         vi),tij)*tij;
108         else
109             T1 = 0;
110             T2 = 0;
111         end
112
113         F = (data.A * exp((rij - d)/data.B) + T1)*nij
114             + T2;

115         data.floor(fi).agents(ai).f = ...
116             data.floor(fi).agents(ai).f + F;
117         data.floor(fi-1).agents(aj).f = ...
118             data.floor(fi-1).agents(aj).f - F;
119
120         end
121     end
122
123     end
124
125 end

```

Listing 1: addAgentRepulsiveForce.m

---

```

1 function data = addDesiredForce(data)
2 %ADDDESIREDFORCE add 'desired' force contribution (towards nearest exit or
3 %staircase)

5 for fi = 1:data.floor_count

7     for ai=1:length(data.floor(fi).agents)

9         % get agent's data
10        p = data.floor(fi).agents(ai).p;
11        m = data.floor(fi).agents(ai).m;
12        v0 = data.floor(fi).agents(ai).v0;

```

```

13     v = data.floor(fi).agents(ai).v;

15
16     % get direction towards nearest exit
17     ex = lerp2(data.floor(fi).img_dir_x, p(1), p(2));
18     ey = lerp2(data.floor(fi).img_dir_y, p(1), p(2));
19     e = [ex ey];

21     % get force
22     Fi = m * (v0*e - v)/data.tau;
23
24     % add force
25     data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
26   end
27 end

```

Listing 2: addDesiredForce.m

```

function data = addWallForce(data)
%ADDWALLFORCE adds wall's force contribution to each agent

for fi = 1:data.floor_count

    for ai=1:length(data.floor(fi).agents)
        % get agents data
        p = data.floor(fi).agents(ai).p;
        ri = data.floor(fi).agents(ai).r;
        vi = data.floor(fi).agents(ai).v;

        % get direction from nearest wall to agent
        nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
        ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));

        % get distance to nearest wall
        diW = lerp2(data.floor(fi).img_wall_dist, p(1), p(2));

        % get perpendicular and tangential unit vectors
        niW = [ nx ny];
        tiW = [-ny nx];

        % calculate force
        if diW < ri
            T1 = data.k * (ri - diW);
            T2 = data.kappa * (ri - diW) * dot(vi, tiW) * tiW;
        else
            T1 = 0;
            T2 = 0;
        end
        Fi = (data.A * exp((ri-diW)/data.B) + T1)*niW - T2;
    end
end

```

```

34      % add force to agent's current force
35      data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
36    end
end

```

Listing 3: addWallForce.m

```

function data = applyForcesAndMove(data)
%APPLYFORCESANDMOVE apply current forces to agents and move them using
%the timestep and current velocity
n_velocity_clamps = 0;
% loop over all floors higher than exit floor
for fi = data.floor_exit:data.floor_count

    % init logical arrays to indicate agents that change the floor or exit
    % the simulation
    floorchange = false(length(data.floor(fi).agents),1);
    exited = false(length(data.floor(fi).agents),1);

    % loop over all agents
    for ai=1:length(data.floor(fi).agents)
        % add current force contributions to velocity
        v = data.floor(fi).agents(ai).v + data.dt * ...
            data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;

        % clamp velocity
        if norm(v) > data.v_max
            v = v / norm(v) * data.v_max;
            n_velocity_clamps = n_velocity_clamps + 1;
        end

        % get agent's new position
        newp = data.floor(fi).agents(ai).p + ...
            v * data.dt / data.meter_per_pixel;

        % if the new position is inside a wall, remove perpendicular
        % component of the agent's velocity
        if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
            data.floor(fi).agents(ai).r

            % get agent's position
            p = data.floor(fi).agents(ai).p;

            % get wall distance gradient (which is off course perpendicular
            % to the nearest wall)
            nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
            ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));

```

```

n = [nx ny];
44
% project out perpendicular component of velocity vector
46 v = v - dot(n,v)/dot(n,n)*n;

48 % get agent's new position
49 newp = data.floor(fi).agents(ai).p + ...
50     v * data.dt / data.meter_per_pixel;
end
52
% check if agents position is ok
54 % repositioning after 50 times clogging
55 % deleting if agent has a NaN position
56 if ~isnan(newp)
    if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
        newp = data.floor(fi).agents(ai).p;
        v = [0 0];
57        data.floor(fi).agents(ai).clogged =
            data.floor(fi).agents(ai).clogged + 1;
58        fprintf('WARNING: clogging agent %i on floor %i (%i).
            Position
            (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
59        if data.floor(fi).agents(ai).clogged >= 40
60            nx = rand(1)*2 - 1;
61            ny = rand(1)*2 - 1;
62            n = [nx ny];
63            v = n*data.v_max/2;
64            fprintf('WARNING: agent %i on floor %i velocity set
                random to get out of wall. Position
                (%f,%f).\n',ai,fi,newp(1),newp(2))
65
66            % get agent's new position
67            newp = data.floor(fi).agents(ai).p + ...
68                v * data.dt / data.meter_per_pixel;
69            if isnan(newp)
                % get rid of disturbing agent
70                fprintf('WARNING: position of an agent is NaN!
                    Deleted this agent.\n')
71                exited(ai) = 1;
72                data.agents_exited = data.agents_exited +1;
73                data.output.deleted_agents=data.output.deleted_agents+1;
74                newp = [1 1];
75            end
76        end
77    end
78 else
    % get rid of disturbing agent
79    fprintf('WARNING: position of an agent is NaN! Deleted this
        agent.\n')
80    exited(ai) = 1;

```

```

86         data.agents_exited = data.agents_exited +1;
87         data.output.deleted_agents=data.output.deleted_agents+1;
88         newp = [1 1];
89     end
90
92     % update agent's velocity and position
93     data.floor(fi).agents(ai).v = v;
94     data.floor(fi).agents(ai).p = newp;
95
96     % reset forces for next timestep
97     data.floor(fi).agents(ai).f = [0 0];
98
99     % check if agent reached a staircase down and indicate floor change
100    if data.floor(fi).img_stairs_down(round(newp(1)), round(newp(2)))
101        floorchange(ai) = 1;
102    end
103
104    % check if agent reached an exit
105    if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
106        exited(ai) = 1;
107        data.agents_exited = data.agents_exited +1;
108
109        %
110        fprintf('agent exited from upper loop\n');
111
112        %save current exit nr
113        data.current_exit = data.exit_nr(round(newp(1)),
114                                         round(newp(2)));
115
116        %
117        fprintf(int2str(data.current_exit));
118
119        %update exit_left
120        data.exit_left(1,data.current_exit) =
121            data.exit_left(1,data.exit_nr(round(newp(1)),
122                           round(newp(2)))) - 1;
123
124        %close exit if there is no more free space
125        if data.exit_left(1,data.current_exit) < 1
126
127            %change current exit to wall
128            data.floor(data.floor_exit).img_wall =
129                data.floor(data.floor_exit).img_wall == 1 ...
130                    | (data.exit_nr == (data.current_exit));
131            data.floor(data.floor_exit).img_exit =
132                data.floor(data.floor_exit).img_exit == 1 ...
133                    & (data.exit_nr ~= (data.current_exit));
134
135            %redo initEscapeRoutes and initWallForces with new exit
136            % and wall parameters
137            data = initEscapeRoutes(data);

```

```

130         data = initWallForces(data);

132 %           fprintf('new routes from upper loop\n');

134     end
135   end
136 end

138 % add appropriate agents to next lower floor
139 if fi > data.floor_exit
140     data.floor(fi-1).agents = [data.floor(fi-1).agents
141                               data.floor(fi).agents(floorchange)];
142 end

143 % delete these and exited agents
144 data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
145 end

146

147

148

149

150 % loop over all floors lower than exit floor
151 for fi = 1:data.floor_exit

152 % init logical arrays to indicate agents that change the floor or exit
153 % the simulation
154 floorchange = false(length(data.floor(fi).agents),1);
155 exited = false(length(data.floor(fi).agents),1);

156 % loop over all agents
157 for ai=1:length(data.floor(fi).agents)
158     % add current force contributions to velocity
159     v = data.floor(fi).agents(ai).v + data.dt * ...
160       data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;

161     % clamp velocity
162     if norm(v) > data.v_max
163         v = v / norm(v) * data.v_max;
164         n_velocity_clamps = n_velocity_clamps + 1;
165     end

166     % get agent's new position
167     newp = data.floor(fi).agents(ai).p + ...
168           v * data.dt / data.meter_per_pixel;

169     % if the new position is inside a wall, remove perpendicular
170     % component of the agent's velocity
171     if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
172         data.floor(fi).agents(ai).r

```

```

180      % get agent's position
181      p = data.floor(fi).agents(ai).p;
182
183      % get wall distance gradient (which is of course perpendicular
184      % to the nearest wall)
185      nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
186      ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
187      n = [nx ny];
188
189      % project out perpendicular component of velocity vector
190      v = v - dot(n,v)/dot(n,n)*n;
191
192      % get agent's new position
193      newp = data.floor(fi).agents(ai).p + ...
194          v * data.dt / data.meter_per_pixel;
195
196  end
197
198  % check if agents position is ok
199  % repositioning after 50 times clogging
200  % deleting if agent has a NaN position
201  if ~isnan(newp)
202      if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
203          newp = data.floor(fi).agents(ai).p;
204          v = [0 0];
205          data.floor(fi).agents(ai).clogged =
206              data.floor(fi).agents(ai).clogged + 1;
207          fprintf('WARNING: clogging agent %i on floor %i (%i).
208                  Position
209                  (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
210
211  if data.floor(fi).agents(ai).clogged >= 40
212      nx = rand(1)*2 - 1;
213      ny = rand(1)*2 - 1;
214      n = [nx ny];
215      v = n*data.v_max/2;
216
217      fprintf('WARNING: agent %i on floor %i velocity set
218                  random to get out of wall. Position
219                  (%f,%f).\n',ai,fi,newp(1),newp(2))
220
221      % get agent's new position
222      newp = data.floor(fi).agents(ai).p + ...
223          v * data.dt / data.meter_per_pixel;
224
225      if isnan(newp)
226          % get rid of disturbing agent
227          fprintf('WARNING: position of an agent is NaN!
228                  Deleted this agent.\n')
229          exited(ai) = 1;
230          data.agents_exited = data.agents_exited +1;
231          data.output.deleted_agents=data.output.deleted_agents+1;

```

```

224
225         newp = [1 1];
226     end
227 end
228 else
229     % get rid of disturbing agent
230     fprintf('WARNING: position of an agent is NaN! Deleted this
231         agent.\n')
232     exited(ai) = 1;
233     data.agents_exited = data.agents_exited +1;
234     data.output.deleted_agents=data.output.deleted_agents+1;
235     newp = [1 1];
236 end

237
238     % update agent's velocity and position
239     data.floor(fi).agents(ai).v = v;
240     data.floor(fi).agents(ai).p = newp;

241
242     % reset forces for next timestep
243     data.floor(fi).agents(ai).f = [0 0];
244
245     % check if agent reached a staircase up and indicate floor change
246     if data.floor(fi).img_stairs_up(round(newp(1)), round(newp(2)))
247         floorchange(ai) = 1;
248     end

249     % check if agent reached an exit
250     if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
251         exited(ai) = 1;
252         data.agents_exited = data.agents_exited +1;
253
254         %
255         fprintf('agent exited from lower loop\n');

256         %save current exit nr
257         data.current_exit = data.exit_nr(round(newp(1)),
258                                         round(newp(2)));

259
260         %update exit_left
261         data.exit_left(1,data.current_exit) =
262             data.exit_left(1,data.exit_nr(round(newp(1)),
263                           round(newp(2)))) - 1;

264
265             %close exit if there is no more free space
266             if data.exit_left(1,data.current_exit) < 1

267                 %change current exit to wall
268                 data.floor(data.floor_exit).img_wall =
269                     data.floor(data.floor_exit).img_wall == 1 ...
270                         | (data.exit_nr == (data.current_exit));

```

```

268         data.floor(data.floor_exit).img_exit =
269             data.floor(data.floor_exit).img_exit == 1 ...
270                 & (data.exit_nr ~= (data.current_exit));
271
272         %redo initEscapeRoutes and initWallForces with new exit
273         % and wall parameters
274         data = initEscapeRoutes(data);
275         data = initWallForces(data);
276
277         fprintf('new routes from lower loop\n');
278
279     end
280
281     end
282
283     % add appropriate agents to next lower floor
284     if fi < data.floor_exit
285         data.floor(fi+1).agents = [data.floor(fi+1).agents ...
286                                     data.floor(fi).agents(floorchange)];
287     end
288
289     % delete these and exited agents
290     data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
291
292     % if n_velocity_clamps > 0
293     %     fprintf(['WARNING: clamped velocity of %d agents, ...
294     %             \'possible simulation instability.\n'], n_velocity_clamps);
295 % end

```

Listing 4: applyForcesAndMove.m

```

function val = checkForIntersection(data, floor_idx, agent_idx)
% check an agent for an intersection with another agent or a wall
% the check is kept as simple as possible
%
% arguments:
%   data          global data structure
%   floor_idx     which floor to check
%   agent_idx     which agent on that floor
%   agent_new_pos vector: [x,y], desired agent position to check
%
% return:
%   0            for no intersection
%   1            has an intersection with wall
%   2            with another agent
%
16 val = 0;

```

```

18 p = data.floor(floor_idx).agents(agent_idx).p;
r = data.floor(floor_idx).agents(agent_idx).r;
20
21 % check for agent intersection
22 for i=1:length(data.floor(floor_idx).agents)
23     if i~=agent_idx
24         if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
25             ...
26             <= r + data.floor(floor_idx).agents(i).r
27             val=2;
28             return;
29     end
30 end
31
32 % check for wall intersection
33 if lerp2(data.floor(floor_idx).img_wall_dist, p(1), p(2)) < r
34     val = 1;
35 end

```

---

Listing 5: checkForIntersection.m

```

1 mex 'fastSweeping.c'
2 mex 'getNormalizedGradient.c'
3 mex 'lerp2.c'
4 mex 'createRangeTree.c'
5 mex 'rangeQuery.c'

```

---

Listing 6: compileC.m

```

1 function data = initAgents(data)
2
3 % place agents randomly in desired spots, without overlapping
4
5
6
7 function radius = getAgentRadius()
8     %radius of an agent in meters
9     radius = data.r_min + (data.r_max-data.r_min)*rand();
10 end
11
12 data.agents_exited = 0; %how many agents have reached the exit
13 data.total_agent_count = 0;
14
15 floors_with_agents = 0;
16 agent_count = data.agents_per_floor;
17 for i=1:data.floor_count
18     data.floor(i).agents = [];
19     [y,x] = find(data.floor(i).img_spawn);

```

---

```

21     if ~isempty(x)
22         floors_with_agents = floors_with_agents + 1;
23         for j=1:agent_count
24             cur_agent = length(data.floor(i).agents) + 1;
25
26             % init agent
27             data.floor(i).agents(cur_agent).r = getAgentRadius();
28             data.floor(i).agents(cur_agent).v = [0, 0];
29             data.floor(i).agents(cur_agent).f = [0, 0];
30             data.floor(i).agents(cur_agent).m = data.m;
31             data.floor(i).agents(cur_agent).v0 = data.v0;
32             data.floor(i).agents(cur_agent).clogged = 0; %to check if
33                 agent is hanging in the wall
34
35             tries = 10;
36             while tries > 0
37                 % randomly pick a spot and check if it's free
38                 idx = randi(length(x));
39                 data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
40                 if checkForIntersection(data, i, cur_agent) == 0
41                     tries = -1; % leave the loop
42                 end
43                 tries = tries - 1;
44             end
45             if tries > -1
46                 %remove the last agent
47                 data.floor(i).agents = data.floor(i).agents(1:end-1);
48             end
49         end
50         data.total_agent_count = data.total_agent_count +
51             length(data.floor(i).agents);
52
53         if length(data.floor(i).agents) ~= agent_count
54             fprintf(['WARNING: could only place %d agents on floor %d , ...
55                     instead of the desired %d.\n'], ...
56                     length(data.floor(i).agents), i, agent_count);
57         end
58     end
59     if floors_with_agents==0
60         error('no spots to place agents!');
61     end

```

Listing 7: initAgents.m

---

```

function data = initEscapeRoutes(data)
%INITESCAPEROUTES Summary of this function goes here

```

```

% Detailed explanation goes here
4
for i=1:data.floor_count
6
    boundary_data = zeros(size(data.floor(i).img_wall));
8
    boundary_data(data.floor(i).img_wall) = 1;
10 if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;
12 elseif i>data.floor_exit
14     boundary_data(data.floor(i).img_stairs_down) = -1;
16 else
18     boundary_data(data.floor(i).img_exit) = -1;
end
20 exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
22 [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
    getNormalizedGradient(boundary_data, -exit_dist);
end

```

Listing 8: initEscapeRoutes.m

---

```

function data = initialize(config)
2 % initialize the internal data from the config data
%
4 % arguments:
% config      data structure from loadConfig()
6 %
% return:
8 % data       data structure: all internal data used for the main loop
%
10 %           all internal data is stored in pixels NOT in meters

12
data = config;
14
%for convenience
16 data.pixel_per_meter = 1/data.meter_per_pixel;

18 fprintf('Init escape routes...\n');
data = initEscapeRoutes(data);
20 fprintf('Init wall forces...\n');
data = initWallForces(data);
22 fprintf('Init agents...\n');
data = initAgents(data);
24
% maximum influence of agents on each other
26

```

```

    data.r_influence = data.pixel_per_meter * ...
28      fzero(@(r) data.A * exp((2*data.r_max-r)/data.B) - 1e-4, data.r_max);

30 fprintf('Init plots...\n');
%init the plots
32 %exit plot
    data.figure_exit=figure;
34 hold on;
    axis([0 data.duration 0 data.total_agent_count]);
36 title(sprintf('agents that reached the exit (total agents: %i)', ...
    data.total_agent_count));

38 % floors plot
    data.figure_floors=figure;
40 % figure('units','normalized','outerposition',[0 0 1 1])
    data.figure_floors_subplots_w = data.floor_count;
42 data.figure_floors_subplots_h = 4;
    for i=1:config.floor_count
        data.floor(i).agents_on_floor_plot =
            subplot(data.figure_floors_subplots_h,
            data.figure_floors_subplots_w, 3*data.floor_count - i+1 +
            data.figure_floors_subplots_w);
        if i == config.floor_exit - 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                data.figure_floors_subplots_w,
                [(2*config.floor_count+1):3*config.floor_count]);
        elseif i == config.floor_exit
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                data.figure_floors_subplots_w,
                [(config.floor_count+1):2*config.floor_count]);
        elseif i == config.floor_exit + 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                data.figure_floors_subplots_w, [1:config.floor_count]);
        end
52    end

54 % init output matrizes
    data.output = struct;
56 data.output.config = config;
    data.output.agents_per_floor =
        ones(data.floor_count,data.duration/data.dt).*(-1);
58 data.output.exit_left = zeros(data.exit_count,data.duration/data.dt);

60 % prepare output file name
    data.output_file_name = ['output_' data.frame_basename];
62 % prepare video file name

```

```

64 data.video_file_name = [ 'video_ ' data.frame_basename '.avi' ];
66 % set deleted_agents to zero
data.output.deleted_agents = 0;

```

Listing 9: initialize.m

```

function data = initWallForces(data)
%INITWALLFORCES init wall distance maps and gradient maps for each floor

for i=1:data.floor_count

    % init boundary data for fast sweeping method
    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) = -1;

    % get wall distance
    wall_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    data.floor(i).img_wall_dist = wall_dist;

    % get normalized wall distance gradient
    [data.floor(i).img_wall_dist_grad_x, ...
    data.floor(i).img_wall_dist_grad_y] = ...
    getNormalizedGradient(boundary_data, wall_dist-data.meter_per_pixel);
end

```

Listing 10: initWallForces.m

```

function config = loadConfig(config_file)
% load the configuration file
%
% arguments:
% config_file      string, which configuration file to load
%
%

% get the path from the config file -> to read the images
config_path = fileparts(config_file);
if strcmp(config_path, '') == 1
    config_path = '.';
end

fid = fopen(config_file);
input = textscan(fid, '%s=%s');
fclose(fid);

keynames = input{1};
values = input{2};

%convert numerical values from string to double

```

```

23 v = str2double(values);
24 idx = ~isnan(v);
25 values(idx) = num2cell(v(idx));

27 config = cell2struct(values, keynames);

29
30 % read the images
31 for i=1:config.floor_count

32     %building structure
33     file = config.(sprintf('floor_%d_build', i));
34     file_name = [config_path '/ file];
35     img_build = imread(file_name);

36     % decode images
37     config.floor(i).img_wall = (img_build(:, :, 1) == 0 ...
38                                 & img_build(:, :, 2) == 0 ...
39                                 & img_build(:, :, 3) == 0);

40     config.floor(i).img_spawn = (img_build(:, :, 1) == 255 ...
41                                 & img_build(:, :, 2) == 0 ...
42                                 & img_build(:, :, 3) == 255);

43 %second possibility:
44 %pixel is exit if 1-->0, 3-->0, and if 2 is between 255 and 230 or if no
45 %red or blue

46     config.floor(i).img_exit = (img_build(:, :, 1) == 0 ...
47                                 & img_build(:, :, 2) ~= 0 ...
48                                 & img_build(:, :, 3) == 0);

49
50     config.floor(i).img_stairs_up = (img_build(:, :, 1) == 255 ...
51                                     & img_build(:, :, 2) == 0 ...
52                                     & img_build(:, :, 3) == 0);

53     config.floor(i).img_stairs_down = (img_build(:, :, 1) == 0 ...
54                                     & img_build(:, :, 2) == 0 ...
55                                     & img_build(:, :, 3) == 255);

56
57
58
59
60
61
62
63

64 if i == config.floor_exit

65     %make the exit_nr matrix where the number of exit is indicated in
66     %each
67     %pixel
68
69     %make a zeroes matrix as big as img_exit
70     config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));
71

```

```

73     %make a zeros vector as long as floor_exit
74     config.exit_left = zeros(1,config.exit_count);
75
76     %loop over all exits
77     for e=1:config.exit_count
78
78         %build the exit_nr matrix
79         config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0
80             & img_build(:, :, 2) == (256-e) & img_build(:, :, 3) == 0 )
81
82         %build the exit_left matrix
83         config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));
84
85     end
86 end
87
88 %init the plot image here, because this won't change
89 config.floor(i).img_plot = 5*config.floor(i).img_wall ...
90     + 4*config.floor(i).img_stairs_up ...
91     + 3*config.floor(i).img_stairs_down ...
92     + 2*config.floor(i).img_exit ...
93     + 1*config.floor(i).img_spawn;
94 config.color_map = [1 1 1; 0.9 0.9 0.9; 0 1 0; 0.4 0.4 1; 1 0.4 0.4; 0
95 0 0];
96 end

```

Listing 11: loadConfig.m

---

```

1 function plotAgentsPerFloor(data, floor_idx)
2 %plot time vs agents on floor
3
4 h = subplot(data.floor(floor_idx).agents_on_floor_plot);
5
6 set(h, 'position',[0.05+(data.floor_count -
7     floor_idx)/(data.figure_floors_subplots_w+0.2), ...
8     0.05, 1/(data.figure_floors_subplots_w*1.2), 0.3-0.05 ]);
9
10 if floor_idx~=data.floor_count
11     set(h, 'ytick',[]) %hide y-axis label
12 end
13
14 axis([0 data.time+data.dt 0 data.agents_per_floor*2]);
15
16 %axis([0 data.duration 0 data.agents_per_floor*2]);
17
18 hold on;
19 plot(data.time, length(data.floor(floor_idx).agents), 'b-');
20 hold off;

```

```

20 title(sprintf('%i', floor_idx));

```

Listing 12: plotAgentsPerFloor.m

---

```

function plotExitedAgents(data)
%plot time vs exited agents

hold on;
plot(data.time, data.agents_exited, 'r-');
hold off;

```

---

Listing 13: plotExitedAgents.m

---

```

function plotFloor(data, floor_idx)
if floor_idx == data.floor_exit-1 || floor_idx == data.floor_exit ||
    floor_idx == data.floor_exit+1
    h=subplot(data.floor(floor_idx).building_plot);

set(h,
    'position',[0,0.35+0.65/3*(floor_idx-data.floor_exit+1),1,0.65/3-0.005]);

hold off;
% the building image
imagesc(data.floor(floor_idx).img_plot);
hold on;

%plot options
colormap(data.color_map);
axis equal;
axis manual; %do not change axis on window resize

set(h, 'Visible', 'off')
% title(sprintf('floor %i', floor_idx))

% plot agents
if ~isempty(data.floor(floor_idx).agents)
    ang = [linspace(0,2*pi, 10) nan];
    rmul = [cos(ang) sin(ang)] * data.pixel_per_meter;
    draw = cell2mat(arrayfun(@(a) repmat(a.p,length(ang),1) + a.r*rmul, ...
        data.floor(floor_idx).agents, 'UniformOutput', false));
    line(draw(:,2), draw(:,1), 'Color', 'r');
end

hold off;
end
end

```

---

Listing 14: plotFloor.m

```

% post processing of output.mat data from simulation
2 % to run, you need to load the output first:
3 % load('output_FILENAME');
4
5 % tabula rasa
6 clc
7
8 % read in data from output
9 agents_per_floor = output.agents_per_floor;
10 config = output.config;
11 exit_left = output.exit_left;
12 simulation_time_real = output.simulation_time;
13 dt = config.dt;
14 deleted_agents = output.deleted_agents;
15
16
17 % get users screen size
18 screen_size = get(0, 'ScreenSize');
19
20 % agents on boat
21 agents_on_boat = sum(agents_per_floor(:,1:1:length(agents_per_floor)));
22
23 % check if whole simulation was performed
24 steps=config.duration/dt-1;
25 for i=1:steps
26     if agents_on_boat(i)<0
27         steps=i-2;
28         break
29     end
30 end
31
32 simulation_time_sim = steps*dt;
33
34 % recalculate agents on boat
35 agents_on_boat = sum(agents_per_floor(:,1:1:steps));
36 agents_start = agents_on_boat(1);
37 agents_left = agents_start-agents_on_boat;
38
39 % find out t10, t50, t90, t100
40 t10=0;
41 for i=1:steps
42     if agents_left(i)<agents_start/10
43         t10=t10+dt;
44     end
45 end
46 if t10~=0
47     t10=t10+dt;
48 end

```

```

50 t50=0;
52   for i=1:steps
53     if agents_left(i)<agents_start/2
54       t50=t50+dt;
55   end
56 end
57 if t50~=0
58   t50=t50+dt;
59 end

60 t90=0;
61 for i=1:steps
62   if agents_left(i)<agents_start*0.9
63     t90=t90+dt;
64   end
65 end
66 if t90~=0
67   t90=t90+dt;
68 end

70 t95=0;
71 for i=1:steps
72   if agents_left(i)<agents_start*0.95
73     t95=t95+dt;
74   end
75 end
76 if t95~=0
77   t95=t95+dt;
78 end

80 t100=0;
81 if agents_left==agents_start
82   for i=1:steps
83     if agents_left(i)<agents_start
84       t100=t100+dt;
85     end
86   end
87 end

88 % create time axis
89 if t100~=0
90   time = [0:dt:t100];
91 else
92   time = [0:dt:simulation_time_sim];
93 end
94 steps = length(time);

95 % recalculate agents on boat
96 agents_on_boat = sum(agents_per_floor(:,1:1:steps));
97 agents_start = agents_on_boat(1);

```

```

100 agents_left = agents_start-agents_on_boat;
agents_per_floor = agents_per_floor(:,1:1:steps);
102 exit_left = exit_left(:,1:1:steps);

104 % plot agents left over time
f1 = figure;
106 hold on
grid on
108 set(gca,'XTick',[1:1:8], 'FontSize',16)
plot(time/60,agents_left/agents_start*100, 'LineWidth', 2)
110 axis([0 8 0 100])
title(sprintf('rescued agents (of total %i agents)',agents_start));
112 xlabel('time [min]')
ylabel('rescued agents out of all agents [%]')

114 % plot agents_per_floor over time
116 f2 = figure;
hold on
118 grid on
set(gca,'XTick',[1:1:8], 'FontSize',16)
120 list = cell(config.floor_count,1);
color = hsv(config.floor_count);
122 color(config.floor_exit,:)= [0 0 0];
for i=1:config.floor_count
    plot(time/60,agents_per_floor(i,:), 'LineWidth', 2, 'color',color(i,:))
    list{i} = [sprintf('floor %i',i)];
end
legend(list)
128 axis([0 8 0 800])
130 title(sprintf('agents per floor (of total %i agents)',agents_start));
xlabel('time [min]')
132 ylabel('agents per floor')

134 % plot free places in rescue boats over time
f3 = figure;
136 hold on
grid on
138 set(gca,'XTick',[1:1:8], 'FontSize',16)
list = cell(config.exit_count/2,1);
140 color = hsv(config.exit_count/2);
for i=1:config.exit_count/2
    plot(time/60,exit_left(i,:), 'LineWidth', 2, 'color',color(i,:))
    list{i} = [sprintf('boat %i / --- %i',i,i+13)];
end
for i=config.exit_count/2+1:config.exit_count
    plot(time/60,exit_left(i,:), '--', 'LineWidth',
        2, 'color',color(i-config.exit_count/2,:))
end
148 legend(list)

```

```

150 axis([0 8 0 200])
151 title('rescue boat capacity');
152 xlabel('time [min]')
153 ylabel('free places on rescue boat')
154
155 % scale plots up to screen size
156 set(f1, 'Position', [0 0 screen_size(3) screen_size(4) ] );
157 set(f2, 'Position', [0 0 screen_size(3) screen_size(4) ] );
158 set(f3, 'Position', [0 0 screen_size(3) screen_size(4) ] );
159
160
161 % print out
162 fprintf('Timestep: %f s\n', dt)
163 fprintf('Steps simulated: %i\n', steps)
164 fprintf('Simulation time: %f min\n', simulation_time_sim/60)
165 fprintf('Agents on ship on start: %i\n', agents_start)
166 fprintf('Agents on ship on simulation end: %i\n', agents_on_boat(end))
167 fprintf('Agents deleted due to NaN-positions: %i\n', deleted_agents)
168
169
170 fprintf('t_10: %f\n', t10)
171 fprintf('t_50: %f\n', t50)
172 fprintf('t_90: %f\n', t90)
173 fprintf('t_95: %f\n', t95)
174 fprintf('t_100: %f\n', t100)

```

Listing 15: plotFloor.m

```

1 function simulate(config_file)
2 % run this to start the simulation
3
4 % start recording the matlab output window for debugging reasons
5 diary log
6
7 if nargin==0
8     config_file='../../data/config1.conf';
9 end
10
11 fprintf('Load config file...\n');
12 config = loadConfig(config_file);
13
14 data = initialize(config);
15
16 data.step = 1;
17 data.time = 0;
18 fprintf('Start simulation...\n');
19
20 % tic until simulation end
21 simstart = tic;

```

```

23 %make video while simulation
24 if data.save_frames==1
25     vidObj=VideoWriter(data.video_file_name);
26     open(vidObj);
27 end

28 while (data.time < data.duration)
29     % tic until timestep end
30     tstart=tic;
31     data = addDesiredForce(data);
32     data = addWallForce(data);
33     data = addAgentRepulsiveForce(data);
34     data = applyForcesAndMove(data);

35     % dump agents_per_floor to output
36     for floor=1:data.floor_count
37         data.output.agents_per_floor(floor,data.step) =
38             length(data.floor(floor).agents);
39     end

40     % dump exit_left to output
41     data.output.exit_left(:,data.step) = data.exit_left';

42     if mod(data.step,data.save_step) == 0

43         % do the plotting
44         set(0,'CurrentFigure',data.figure_floors);
45         for floor=1:data.floor_count
46             plotAgentsPerFloor(data, floor);
47             plotFloor(data, floor);
48         end

49         if data.save_frames==1
50             print('-depsc2',sprintf('frames/%s_%04i.eps', ...
51             data.frame_basename,data.step), data.figure_floors);
52
53         % make video while simulate
54         currFrame=getframe(data.figure_floors);
55         writeVideo(vidObj,currFrame);
56
57     end

58     set(0,'CurrentFigure',data.figure_exit);
59     plotExitedAgents(data);

60     if data.agents_exited == data.total_agent_count
61         fprintf('All agents are now saved (or are they?). Time: %.2f
62             sec\n', data.time);
63         fprintf('Total Agents: %i\n', data.total_agent_count);
64
65
66
67
68
69

```

```

71         print('-depsc2', sprintf('frames/exited_agents_%s.eps', ...
72             data.frame_basename), data.figure_floors);
73         break;
74     end
75
76     % toc of timestep
77     data.telapsed = toc(tstart);
78     % toc of whole simulation
79     data.output.simulation_time = toc(simstart);
80
81     % save output
82     output = data.output;
83     save(data.output_file_name, 'output')
84     fprintf('Frame %i done (took %.3fs; %.3fs out of %.3gs
85             simulated).\n', data.step, data.telapsed, data.time,
86             data.duration);
87
88     end
89
90     % update step
91     data.step = data.step+1;
92
93     % update time
94     if (data.time + data.dt > data.duration)
95         data.dt = data.duration - data.time;
96         data.time = data.duration;
97     else
98         data.time = data.time + data.dt;
99     end
100
101    %make video while simulation
102    close(vidObj);
103
104    % toc of whole simulation
105    data.output.simulation_time = toc(simstart);
106
107    % save complete simulation
108    output = data.output;
109    save('output', 'output')
110    fprintf('Simulation done in %i seconds and saved data to output file.\n',
111           data.output.simulation_time);
112
113    % save diary
114    diary

```

Listing 16: simulate.m

### 9.1.2 C code

```

1 #include <mex.h>
3 #include <string.h>

5 #include "tree_build.c"
#include "tree_query.c"
7 #include "tree_free.c"

9 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
    *prhs[])
{
11     point_t *points;
    tree_t *tree;
13     int m, n;
    uchar *data;
15     int *root_index;

17     if (nlhs < 1)
        return;
19
    points = (point_t*) mxGetPr(prhs[0]);
    m = mxGetM(prhs[0]);
    n = mxGetN(prhs[0]);
23
    if (m != 2)
        mexErrMsgTxt("...");

25     tree = build_tree(points, n);

27     plhs[0] = mxCreateNumericMatrix(tree->first_free + sizeof(int), 1,
        mxUINT8_CLASS, mxREAL);
    data = (uchar*) mxGetPr(plhs[0]);

29     root_index = (int*) data;
    *root_index = tree->root_index;
    memcpy(data + sizeof(int), tree->data, tree->first_free);
31
    free_tree(tree);
33 }
35 }
```

Listing 17: createRangeTree.c

```

1 #include "mex.h"

3 #include <math.h>

5 #if defined __GNUC__ && defined __FAST_MATH__ && !defined __STRICT_ANSI__
#define MIN(i, j) fmin(i, j)
```

```

7 #define MAX(i, j) fmax(i, j)
  #define ABS(i)      fabs(i)
9 #else
  #define MIN(i, j) ((i) < (j) ? (i) : (j))
11 #define MAX(i, j) ((i) > (j) ? (i) : (j))
  #define ABS(i)      ((i) < 0.0 ? -(i) : (i))
13 #endif

15
17 #define SOLVE_AND_UPDATE    udiff = uxmin - uymin; \
18     if (ABS(udiff) >= 1.0) \
19     { \
20         up = MIN(uxmin, uymin) + 1.0; \
21     } \
22     else \
23     { \
24         up = (uxmin + uymin + sqrt(2.0 - udiff * \
25             udiff)) / 2.0; \
26         up = MIN(uij, up); \
27     } \
28     err_loc = MAX(ABS(uij - up), err_loc); \
29     u[ij] = up;

30 #define I_STEP(_uxmin, _uymin, _st) if (boundary[ij] == 0.0) \
31     { \
32         uij = un; \
33         un = u[ij + _st]; \
34         uxmin = _uxmin; \
35         uymin = _uymin; \
36         SOLVE_AND_UPDATE \
37         ij += _st; \
38     } \
39     else \
40     { \
41         up = un; \
42         un = u[ij + _st]; \
43         ij += _st; \
44     }
45
46
47 #define I_STEP_UP(_uxmin, _uymin)   I_STEP(_uxmin, _uymin, 1)
48 #define I_STEP_DOWN(_uxmin, _uymin) I_STEP(_uxmin, _uymin, -1)

50 #define UX_NEXT un
51 #define UX_PREV up
52 #define UX_BOTH MIN(UX_PREV, UX_NEXT)

53 #define UY_RIGHT u[ij + m]

```

```

#define UY_LEFT u[ij - m]
#define UY_BOTH MIN(UY_LEFT, UY_RIGHT)

59

61 static void iteration(double *u, double *boundary, int m, int n, double
    *err)
{
63     int i, j, ij;
64     int m2, n2;
65     double up, un, uij, uxmin, uymin, udifff, err_loc;

67     m2 = m - 2;
68     n2 = n - 2;
69
70     *err = 0.0;
71     err_loc = 0.0;

73     /* first sweep */
74     /* i = 0, j = 0 */
75     ij = 0;
76     un = u[ij];
77     I_STEP_UP(UX_NEXT, UY_RIGHT)

79     /* i = 1->m2, j = 0 */
80     for (i = 1; i <= m2; ++i)
81         I_STEP_UP(UX_BOTH, UY_RIGHT)

83     /* i = m-1, j = 0 */
84     I_STEP_UP(UX_PREV, UY_RIGHT)

85     /* i = 0->m-1, j = 1->n2 */
86     for (j = 1; j <= n2; ++j)
87     {
88         I_STEP_UP(UX_NEXT, UY_BOTH)

89         for (i = 1; i <= m2; ++i)
90             I_STEP_UP(UX_BOTH, UY_BOTH)

91         I_STEP_UP(UX_PREV, UY_BOTH)
92     }

93     /* i = 0, j = n-1 */
94     I_STEP_UP(UX_NEXT, UY_LEFT)

95     /* i = 1->m2, j = n-1 */
96     for (i = 1; i <= m2; ++i)
97         I_STEP_UP(UX_BOTH, UY_LEFT)

98     /* i = m-1, j = n-1 */
99
100
101
102
103

```

```

105     I_STEP_UP(UX_PREV, UY_LEFT)

107
109     /* sweep 2 */
110     /* i = 0, j = n-1 */
111     ij = (n-1)*m;
112     un = u[ij];
113     I_STEP_UP(UX_NEXT, UY_LEFT)

115     /* i = 1->m2, j = n-1 */
116     for (i = 1; i <= m2; ++i)
117         I_STEP_UP(UX_BOTH, UY_LEFT)

119     /* i = m-1, j = n-1 */
120     I_STEP_UP(UX_PREV, UY_LEFT)

121     /* i = 0->m-1, j = n2->1 */
122     for (j = n2; j >= 1; --j)
123     {
124         ij = j*m;
125         un = u[ij];
126         I_STEP_UP(UX_NEXT, UY_BOTH)

127         for (i = 1; i <= m2; ++i)
128             I_STEP_UP(UX_BOTH, UY_BOTH)

129         I_STEP_UP(UX_PREV, UY_BOTH)
130     }

133     /* i = 0, j = 0 */
134     ij = 0;
135     un = u[ij];
136     I_STEP_UP(UX_NEXT, UY_RIGHT)

139     /* i = 1->m2, j = 0 */
140     for (i = 1; i <= m2; ++i)
141         I_STEP_UP(UX_BOTH, UY_RIGHT)

143     /* i = m-1, j = 0 */
144     I_STEP_UP(UX_PREV, UY_RIGHT)

145
146     /* sweep 3 */
147     /* i = m-1, j = n-1 */
148     ij = m*n - 1;
149     un = u[ij];
150     I_STEP_DOWN(UX_NEXT, UY_LEFT)

151
152     /* i = m2->1, j = n-1 */
153     for (i = m2; i >= 1; --i)
154         I_STEP_DOWN(UX_BOTH, UY_LEFT)

```

```

155      /* i = 0, j = n-1 */
157      I_STEP_DOWN(UX_PREV, UY_LEFT)

159      /* i = m-1->0, j = n2->1 */
160      for (j = n2; j >= 1; --j)
161      {
162          I_STEP_DOWN(UX_NEXT, UY_BOTH)

163          for (i = m2; i >= 1; --i)
164              I_STEP_DOWN(UX_BOTH, UY_BOTH)

165          I_STEP_DOWN(UX_PREV, UY_BOTH)
166      }

167      /* i = m-1, j = 0 */
168      I_STEP_DOWN(UX_NEXT, UY_RIGHT)

169      /* i = m2->1, j = 0 */
170      for (i = m2; i >= 1; --i)
171          I_STEP_DOWN(UX_BOTH, UY_RIGHT)

172      /* i = 0, j = 0 */
173      I_STEP_DOWN(UX_PREV, UY_RIGHT)

174      /* sweep 4 */
175      /* i = m-1, j = 0 */
176      ij = m - 1;
177      un = u[ij];
178      I_STEP_DOWN(UX_NEXT, UY_RIGHT)

179      /* i = m2->1, j = 0 */
180      for (i = m2; i >= 1; --i)
181          I_STEP_DOWN(UX_BOTH, UY_RIGHT)

182      /* i = 0, j = 0 */
183      I_STEP_DOWN(UX_PREV, UY_RIGHT)

184      /* i = m-1->0, j = 1->n2 */
185      for (j = 1; j <= n2; ++j)
186      {
187          ij = m - 1 + j*m;
188          un = u[ij];
189          I_STEP_DOWN(UX_NEXT, UY_BOTH)

190          for (i = m2; i >= 1; --i)
191              I_STEP_DOWN(UX_BOTH, UY_BOTH)

192          I_STEP_DOWN(UX_PREV, UY_BOTH)
193      }

```

```

205     /* i = m-1, j = n-1 */
207     ij = m*n - 1;
208     un = u[ij];
209     I_STEP_DOWN(UX_NEXT, UY_LEFT)

211     /* i = m2->1, j = n-1 */
212     for (i = m2; i >= 1; --i)
213         I_STEP_DOWN(UX_BOTH, UY_LEFT)

215     /* i = 0, j = n-1 */
216     I_STEP_DOWN(UX_PREV, UY_LEFT)
217
218     *err = MAX(*err, err_loc);
219 }

220 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
221 *prhs[])
222 {
223     double *u, *boundary;
224     double tol, err;
225     int m, n, entries, max_iter, i;

226     /* Check number of outputs */
227     if (nlhs < 1)
228         return;
229     else if (nlhs > 1)
230         mexErrMsgTxt("At most 1 output argument needed.");

231     /* Get inputs */
232     if (nrhs < 1)
233         mexErrMsgTxt("At least 1 input argument needed.");
234     else if (nrhs > 3)
235         mexErrMsgTxt("At most 3 input arguments used.");
236
237
238
239
240     /* Get boundary */
241     if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
242         mexErrMsgTxt("Boundary field needs to be a full double precision
243                     matrix.");
244
245     boundary = mxGetPr(prhs[0]);
246     m = mxGetM(prhs[0]);
247     n = mxGetN(prhs[0]);
248     entries = m * n;
249
250     /* Get max iterations */
251     if (nrhs >= 2)
252     {

```

```

253     if (!mxIsDouble(prhs[1]) || mxGetM(prhs[1]) != 1 ||
254         mxGetN(prhs[1]) != 1)
255         mexErrMsgTxt("Maximum iteration needs to be positive
256                     integer.");
257     max_iter = (int) *mxGetPr(prhs[1]);
258     if (max_iter <= 0)
259         mexErrMsgTxt("Maximum iteration needs to be positive
260                     integer.");
261 }
262 else
263     max_iter = 20;
264
265 /* Get tolerance */
266 if (nrhs >= 3)
267 {
268     if (!mxIsDouble(prhs[2]) || mxGetM(prhs[2]) != 1 ||
269         mxGetN(prhs[2]) != 1)
270         mexErrMsgTxt("Tolerance needs to be a positive real number.");
271     tol = *mxGetPr(prhs[2]);
272     if (tol < 0)
273         mexErrMsgTxt("Tolerance needs to be a positive real number.");
274 }
275 else
276     tol = 1e-12;
277
278 /* create and init output (distance) matrix */
279 plhs[0] = mxCreateDoubleMatrix(m, n, mxREAL);
280 u = mxGetPr(plhs[0]);
281
282 for (i = 0; i < entries; ++i)
283     u[i] = boundary[i] < 0.0 ? 0.0 : 1.0e10;
284
285 err = 0.0;
286 i = 0;
287 do
288 {
289     iteration(u, boundary, m, n, &err);
290     ++i;
291 } while (err > tol && i < max_iter);
292 }
```

Listing 18: fastSweeping.c

```

1 #include "mex.h"
3 #include <math.h>
5 #define INTERIOR(i, j) (boundary[(i) + m*(j)] == 0)
```

```

7 #define DIST(i, j)  dist[(i) + m*(j)]
8 #define XGRAD(i, j) xgrad[(i) + m*(j)]
9 #define YGRAD(i, j) ygrad[(i) + m*(j)]

11 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
                  *prhs[])
{
13     double *xgrad, *ygrad, *boundary, *dist;
14     double dxp, dxm, dyp, dym, xns, yns, nrm;
15     int m, n, i, j, nn;

17     /* Check number of outputs */
18     if (nlhs < 2)
19         mexErrMsgTxt("At least 2 output argument needed.");
20     else if (nlhs > 2)
21         mexErrMsgTxt("At most 2 output argument needed.");

23     /* Get inputs */
24     if (nrhs < 2)
25         mexErrMsgTxt("At least 2 input argument needed.");
26     else if (nrhs > 2)
27         mexErrMsgTxt("At most 2 input argument used.");
28

29

31     /* Get boundary */
32     if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
33         mexErrMsgTxt("Boundary field needs to be a full double precision
                      matrix.");
34
35     boundary = mxGetPr(prhs[0]);
36     m = mxGetM(prhs[0]);
37     n = mxGetN(prhs[0]);

39     /* Get distance field */
40     if (!mxIsDouble(prhs[1]) || mxIsClass(prhs[1], "sparse") ||
41         mxGetM(prhs[1]) != m || mxGetN(prhs[1]) != n)
42         mexErrMsgTxt("Distance field needs to be a full double precision
                      matrix with same dimension as the boundary.");
43
44     dist = mxGetPr(prhs[1]);
45     m = mxGetM(prhs[1]);
46     n = mxGetN(prhs[1]);

47     /* create and init output (gradient) matrices */
48     plhs[0] = mxCreateDoubleMatrix(m, n, mxREAL);
49     plhs[1] = mxCreateDoubleMatrix(m, n, mxREAL);
50     xgrad = mxGetPr(plhs[0]);
51     ygrad = mxGetPr(plhs[1]);

```



```

103         {
104             xns += XGRAD(i-1,j);
105             yns += YGRAD(i-1,j);
106             ++nn;
107         }
108         if (i < m-1 && INTERIOR(i+1,j))
109         {
110             xns += XGRAD(i+1,j);
111             yns += YGRAD(i+1,j);
112             ++nn;
113         }
114         if (j > 0 && INTERIOR(i,j-1))
115         {
116             xns += XGRAD(i,j-1);
117             yns += YGRAD(i,j-1);
118             ++nn;
119         }
120         if (j < n-1 && INTERIOR(i,j+1))
121         {
122             xns += XGRAD(i,j+1);
123             yns += YGRAD(i,j+1);
124             ++nn;
125         }
126         if (nn > 0)
127         {
128             XGRAD(i, j) = xns / nn;
129             YGRAD(i, j) = yns / nn;
130         }
131     }
}

```

Listing 19: getNormalizedGradient.c

```

2 #include <mex.h>

4 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
    *prhs[])
{
6     int m, n, i0, i1, j0, j1, idx00;
7     double *data, *out, x, y, wx0, wy0, wx1, wy1;
8     double d00, d01, d10, d11;

10    if (nlhs < 1)
11        return;
12    else if (nlhs > 1)
13        mexErrMsgTxt("Exactly one output argument needed.");
14    if (nrhs != 3)

```

```

16     mexErrMsgTxt("Exactly three input arguments needed.");
17
18     m = mxGetM(prhs[0]);
19     n = mxGetN(prhs[0]);
20     data = mxGetPr(prhs[0]);
21     x = *mxGetPr(prhs[1]) - 1;
22     y = *mxGetPr(prhs[2]) - 1;
23
24     plhs[0] = mxCreateDoubleMatrix(1, 1, mxREAL);
25     out = mxGetPr(plhs[0]);
26
27     x = x < 0 ? 0 : x > m - 1 ? m - 1 : x;
28     y = y < 0 ? 0 : y > n - 1 ? n - 1 : y;
29     i0 = (int) x;
30     j0 = (int) y;
31     i1 = i0 + 1;
32     i1 = i1 > m - 1 ? m - 1 : i1;
33     j1 = j0 + 1;
34     j1 = j1 > n - 1 ? n - 1 : j1;
35
36     idx00 = i0 + m * j0;
37     d00 = data[idx00];
38     d01 = data[idx00 + m];
39     d10 = data[idx00 + 1];
40     d11 = data[idx00 + m + 1];
41
42     wx1 = x - i0;
43     wy1 = y - j0;
44     wx0 = 1.0 - wx1;
45     wy0 = 1.0 - wy1;
46
47     *out = wx0 * (wy0 * d00 + wy1 * d01) + wx1 * (wy0 * d10 + wy1 * d11);
48 }

```

Listing 20: lerp2.c

```

2 #include <mex.h>
3 #include <string.h>
4
5 #include "tree_build.c"
6 #include "tree_query.c"
7 #include "tree_free.c"
8
9 void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
10 *prhs[])
11 {
12     tree_t *tree;
13     int n, i;
14     int *point_idx, *root_idx;

```

```

14     range_t *range;
15     uchar *data;
16
17     if (nlhs != 1)
18         mexErrMsgTxt("... ");
19
20     if (nrhs < 5)
21         mexErrMsgTxt("... ");
22     else if (nrhs > 5)
23         mexErrMsgTxt("... ");
24
25     data = (uchar*) mxGetPr(prhs[0]);
26
27     tree = (tree_t*) malloc(sizeof(tree_t));
28     tree->first_free = mxGetM(prhs[0]) - sizeof(int);
29     tree->total_size = tree->first_free;
30     root_idx = (int*) data;
31     tree->root_index = *root_idx;
32     tree->data = data + sizeof(int);
33
34     n = mxGetN(prhs[0]);
35     if (n != 1)
36         mexErrMsgTxt("... ");
37
38     range = range_query(tree, *mxGetPr(prhs[1]), *mxGetPr(prhs[2]),
39                          *mxGetPr(prhs[3]), *mxGetPr(prhs[4]));
40
41     plhs[0] = mxCreateNumericMatrix(range->n, 1, mxUINT32_CLASS, mxREAL);
42     point_idx = (int*) mxGetPr(plhs[0]);
43
44     for (i = 0; i < range->n; ++i)
45         point_idx[i] = range->point_idx[i] + 1;
46
47     free_range(range);
48     free(tree);
49 }
```

Listing 21: rangeQuery.c

---

```

1 #ifndef TREE_H
2 #define TREE_H
3
4 #include "tree_types.h"
5
6 /* build a 2D range tree using the given points */
7 tree_t* build_tree(point_t *points, int n);
8
9 /* query a range tree */
10 range_t* range_query(tree_t *tree, double x_min, double x_max, double
11                      y_min, double y_max);
```

```

12 /* free memory of a tree */
13 void free_tree(tree_t *tree);
14
15 /* free memory of a range */
16 void free_range(range_t *range);
17
18 #endif
```

Listing 22: tree.h

```

1 #ifndef TREE_BUILD_H
2 #define TREE_BUILD_H

3 #include "tree.h"

5 /* recursively build a subtree */
6 int build_subtree(tree_t *tree, double *x_vals, const int nx, point_t
7     *points, int *point_idx, const int np);
8
9 /* double comparison for qsort */
10 int compare_double(const void *a, const void *b);

12 /* index array sorting functions, sort point index array by point y
13     coordinates */
14 void index_sort_y(const point_t *points, int *point_idx, const int n);
15 void index_quicksort_y(const point_t *points, int *point_idx, int l, int
16     r);
17 int index_partition_y(const point_t *points, int *point_idx, int l, int r);
18
19 #endif
```

Listing 23: tree\_build.h

```

1
2 #include <assert.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5 #include <string.h>

6 #include "tree_build.h"

7 tree_t* build_tree(point_t *points, int n)
8 {
9     int nx, i, j, *point_idx;
10    double *x_vals;
11    tree_t *tree;
12
13    /* get x coordinate values of all points */
14    x_vals = (double*) malloc(n * sizeof(double));
```

```

17     for (i = 0; i < n; ++i)
18         x_vals[i] = points[i].x;
19
20     /* sort x values */
21     qsort(x_vals, n, sizeof(double), compare_double);
22
23     /* count number of unique x values */
24     nx = 1;
25     for (i = 1; i < n; ++i)
26         if (x_vals[i] != x_vals[i - 1])
27             ++nx;
28
29     /* remove duplicates */
30     j = 0;
31     for (i = 0; i < nx; ++i)
32     {
33         x_vals[i] = x_vals[j];
34         while (x_vals[i] == x_vals[j])
35             ++j;
36     }
37
38     /* create an index array */
39     point_idx = (int*) malloc(n * sizeof(int));
40     for (i = 0; i < n; ++i)
41         point_idx[i] = i;
42
43     /* sort index array by y coordinates of associated points */
44     index_sort_y(points, point_idx, n);
45
46     /* init tree */
47     tree = (tree_t*) malloc(sizeof(tree_t));
48     tree->total_size = n * sizeof(point_t);
49     tree->data = (uchar*) malloc(tree->total_size);
50
51     /* copy point coordinates to tree data */
52     memcpy(tree->data, points, n * sizeof(point_t));
53
54     /* set first free byte and root index of the tree */
55     tree->first_free = n * sizeof(point_t);
56     tree->root_index = tree->first_free;
57
58     /* recursively build tree */
59     build_subtree(tree, x_vals, nx, points, point_idx, n);
60
61     /* free temporaries */
62     free(x_vals);
63     return tree;
64 }
65

```

```

67 int build_subtree(tree_t *tree, double *x_vals, const int nx, point_t
  *points, int *point_idx, const int np)
{
  int i, j, k, nx_left, np_left, node_size, right_idx;
  node_t *node;
  int *node_point_idx, *point_idx_left, *point_idx_right, node_idx;
  uchar *new_data;

73  assert(nx > 0);
75  assert(np > 0);

77  /* allocate memory in the tree data structure */
  node_size = sizeof(node_t) + np * sizeof(int);
79  while (tree->first_free + node_size > tree->total_size)
{
  tree->total_size <= 1;
  new_data = (uchar*) malloc(tree->total_size * sizeof(uchar));
83  for (i = 0; i < tree->first_free; ++i)
    new_data[i] = tree->data[i];
85  free(tree->data);
  tree->data = new_data;
87 }
  node_idx = tree->first_free;
  node = (node_t*) &tree->data[node_idx];
  tree->first_free += node_size;

91  /* set number of stored points */
93  node->np = np;
  node_point_idx = (int*) (node + 1);

95  /* copy point indices to node */
97  memcpy(node_point_idx, point_idx, np * sizeof(int));

99  /* create child node if there is only one x value left, otherwise
   create interior node */
101 if (nx == 1)
{
  node->right_idx = -1;
103  node->x_val = x_vals[0];
}
105 else
{
  /* get median of x values */
107  nx_left = nx >> 1;
109  node->x_val = x_vals[nx_left - 1];

111  /* count points belonging to the left child */
113  np_left = 0;
  for (i = 0; i < np; ++i)
  {

```

```

115         if (points[point_idx[i]].x <= node->x_val)
116             ++np_left;
117     }
118
119     /* allocate memory for children's index arrays */
120     point_idx_left = (int*) malloc(np_left * sizeof(int));
121     point_idx_right = (int*) malloc((np - np_left) * sizeof(int));
122
123     /* fill index arrays */
124     j = 0;
125     k = 0;
126     for (i = 0; i < np; ++i)
127     {
128         if (points[point_idx[i]].x <= node->x_val)
129             point_idx_left[j++] = point_idx[i];
130         else
131             point_idx_right[k++] = point_idx[i];
132     }
133
134     /* free current node's temporary index array */
135     free(point_idx);
136
137     /* build left subtree */
138     build_subtree(tree, x_vals, nx_left, points, point_idx_left,
139                   np_left);
140
141     /* build right subtree and get its root node index */
142     right_idx = build_subtree(tree, x_vals + nx_left, nx - nx_left,
143                               points, point_idx_right, np - np_left);
144     /* update node pointer (could have changed during build_subtree,
145      because of data allocation) */
146     node = (node_t*) &tree->data[node_idx];
147     /* update node's right child index */
148     node->right_idx = right_idx;
149 }
150
151 int compare_double(const void *a, const void *b)
152 {
153     double ad, bd;
154     ad = *((double*) a);
155     bd = *((double*) b);
156     return (ad < bd) ? -1 : (ad > bd) ? 1 : 0;
157 }
158
159 void index_sort_y(const point_t *points, int *point_idx, const int n)
160 {

```

```

        index_quicksort_y(points, point_idx, 0, n - 1);
163 }

165 void index_quicksort_y(const point_t *points, int *point_idx, int l, int r)
{
167     int p;

169     /* quicksort point indices by point y coordinates, don't touch point
       array itself */
171     while (l < r)
172     {
173         p = index_partition_y(points, point_idx, l, r);
174         if (r - p > p - l)
175         {
176             index_quicksort_y(points, point_idx, l, p - 1);
177             l = p + 1;
178         }
179         else
180         {
181             index_quicksort_y(points, point_idx, p + 1, r);
182             r = p - 1;
183         }
184     }
185 }

186 int index_partition_y(const point_t *points, int *point_idx, int l, int r)
187 {
188     int i, j, tmp;
189     double pivot;

190     /* rightmost element is pivot */
191     i = l;
192     j = r - 1;
193     pivot = points[point_idx[r]].y;

194     /* quicksort partition */
195     do
196     {
197         while (points[point_idx[i]].y <= pivot && i < r)
198             ++i;
199
200         while (points[point_idx[j]].y >= pivot && j > l)
201             --j;
202
203         if (i < j)
204         {
205             tmp = point_idx[i];
206             point_idx[i] = point_idx[j];
207             point_idx[j] = tmp;
208         }
209     }

```

```

211     } while (i < j);

213     if (points[point_idx[i]].y > pivot)
214     {
215         tmp = point_idx[i];
216         point_idx[i] = point_idx[r];
217         point_idx[r] = tmp;
218     }

219     return i;
220 }

```

Listing 24: tree\_build.c

```

1 #include <stdlib.h>
3
5 void free_tree(tree_t *tree)
7 {
8     free(tree->data);
9 }

11 void free_range(range_t *range)
12 {
13     free(range->point_idx);
14 }

```

Listing 25: tree\_free.c

```

1 #ifndef TREE_QUERY_H
2 #define TREE_QUERY_H

4 #include "tree_types.h"

6 /* appends a point-index to a range, increases range capacity if needed */
7 void range_append(range_t *range, int idx);

8 /* finds the split node of a given query */
9 int find_split_node(tree_t *tree, int node_idx, range_t *range);

10 /* query the points of a node by a given range by y-coordinate */
11 void range_query_y(tree_t *tree, int node_idx, range_t *range);

14 #endif

```

Listing 26: tree\_query.h

```

1
2 #include <assert.h>
3 #include <stdio.h>
4 #include <stdlib.h>
5
6 #include "tree_query.h"
7
8 #define LEFT_CHILD_IDX(node_idx, node) (node_idx) + sizeof(node_t) +
9     (node)->np * sizeof(int)
10 #define RIGHT_CHILD_IDX(node_idx, node) (node)->right_idx
11 #define NODE_FROM_IDX(tree, node_idx) (node_t*) &(tree)->data[node_idx];
12
13 range_t* range_query(tree_t *tree, double x_min, double x_max, double
14 y_min, double y_max)
15 {
16     int split_node_idx, node_idx;
17     node_t *split_node, *node;
18     range_t *range;
19
20     /* init range */
21     range = (range_t*) malloc(sizeof(range_t));
22     range->min.x = x_min;
23     range->max.x = x_max;
24     range->min.y = y_min;
25     range->max.y = y_max;
26     range->n = 0;
27     range->total_size = 16;
28     range->point_idx = (int*) malloc(range->total_size * sizeof(int));
29
30     /* find split node */
31     split_node_idx = find_split_node(tree, tree->root_index, range);
32     split_node = NODE_FROM_IDX(tree, split_node_idx);
33
34     /* if split node is a child */
35     if (split_node->right_idx == -1)
36     {
37         range_query_y(tree, split_node_idx, range);
38         return range;
39     }
40
41     /* follow left path of the split node */
42     node_idx = LEFT_CHILD_IDX(split_node_idx, split_node);
43     node = NODE_FROM_IDX(tree, node_idx);
44     while (node->right_idx != -1)
45     {
46         if (range->min.x <= node->x_val)
47         {
48             range_query_y(tree, RIGHT_CHILD_IDX(node_idx, node), range);
49             node_idx = LEFT_CHILD_IDX(node_idx, node);
50         }
51     }
52
53     /* copy data from split node to range */
54     for (int i = 0; i < range->n; i++)
55     {
56         range->point_idx[i] = split_node->point_idx[i];
57     }
58
59     /* free memory */
60     free(split_node);
61     free(range->point_idx);
62
63     return range;
64 }

```

```

        }
    else
        node_idx = RIGHT_CHILD_IDX(node_idx, node);
    node = NODE_FROM_IDX(tree, node_idx);
}
range_query_y(tree, node_idx, range);

/* follow right path of the split node */
node_idx = split_node->right_idx;
node = NODE_FROM_IDX(tree, node_idx);
while (node->right_idx != -1)
{
    if (range->max.x > node->x_val)
    {
        range_query_y(tree, LEFT_CHILD_IDX(node_idx, node), range);
        node_idx = RIGHT_CHILD_IDX(node_idx, node);
    }
    else
        node_idx = LEFT_CHILD_IDX(node_idx, node);
    node = NODE_FROM_IDX(tree, node_idx);
}
range_query_y(tree, node_idx, range);

return range;
}

void range_append(range_t *range, int idx)
{
    int *new_point_idx;
    int new_size, i;

    /* just append if there is enough place, otherwise double capacity and
     * append */
    if (range->n < range->total_size)
        range->point_idx[range->n++] = idx;
    else
    {
        new_size = range->total_size << 1;
        new_point_idx = (int*) malloc(new_size * sizeof(int));
        for (i = 0; i < range->n; ++i)
            new_point_idx[i] = range->point_idx[i];
        new_point_idx[range->n++] = idx;
        free(range->point_idx);
        range->point_idx = new_point_idx;
        range->total_size = new_size;
    }
}

int find_split_node(tree_t *tree, int node_idx, range_t *range)
{

```

```

97     node_t *node;

99     node = (node_t*) &tree->data[node_idx];
100    /* check if this node is the split node */
101    if (range->min.x <= node->x_val && range->max.x > node->x_val)
102        return node_idx;
103
104    /* ...or if it is a child (and therefor the split node) */
105    if (node->right_idx == -1)
106        return node_idx;
107
108    /* otherwise search the split node at the left or right of the current
       node */
109    if (range->max.x <= node->x_val)
110        return find_split_node(tree, LEFT_CHILD_IDX(node_idx, node),
111                               range);
112    else
113        return find_split_node(tree, RIGHT_CHILD_IDX(node_idx, node),
114                               range);
114 }

115 void range_query_y(tree_t *tree, int node_idx, range_t *range)
116 {
117     point_t *points;
118     double y;
119     int i, j, k, m, start, end;
120     int *point_idx;
121     node_t *node;

122     node = (node_t*) &tree->data[node_idx];
123     points = (point_t*) tree->data;
124     point_idx = (int*) (node + 1);

125     /* return if all points are outside the range */
126     if (points[point_idx[0]].y > range->max.y || points[point_idx[node->np
127         - 1]].y < range->min.y)
128         return;

129
130     /* binary search for lower end of the range */
131     y = range->min.y;
132     j = 0;
133     k = node->np - 1;
134     while (j != k)
135     {
136         m = (j + k) / 2;
137         if (points[point_idx[m]].y >= y)
138             k = m;
139         else
140             j = m + 1;
141     }

```

```

143     start = j;

145     /* binary search for higher end of the range */
146     y = range->max.y;
147     j = 0;
148     k = node->np - 1;
149     while (j != k)
150     {
151         m = (j + k + 1) / 2;
152         if (points[point_idx[m]].y > y)
153             k = m - 1;
154         else
155             j = m;
156     }
157     end = j;

159     /* append found points to the range */
160     for (i = start; i <= end; ++i)
161         if (points[point_idx[i]].x <= range->max.x)
162             range_append(range, point_idx[i]);
163 }
```

Listing 27: tree\_query.c

---

```

#ifndef TREE_TYPES_H
#define TREE_TYPES_H

typedef unsigned char uchar;

/* 2D point */
typedef struct
{
    double x;
    double y;
} point_t;

/* tree */
typedef struct
{
    /* byte data array with points and nodes */
    uchar *data;

    /* index of first unused byte */
    int first_free;

    /* total number of allocated bytes */
    int total_size;

    /* index of the root node in the data array*/
}
```

```

26     int root_index;
27 } tree_t;
28
29 /* node */
30 typedef struct
31 {
32     /* index of the right child node (left child follows directly after
33      * current) */
34     int right_idx;
35
36     /* number of associated points */
37     int np;
38
39     /* associated x-coordinate value */
40     double x_val;
41 } node_t;
42
43 /* range */
44 typedef struct
45 {
46     /* point index list */
47     int *point_idx;
48
49     /* number of saved indices */
50     int n;
51
52     /* total number of allocated indices */
53     int total_size;
54
55     /* minimum range point */
56     point_t min;
57
58     /* maximum range point */
59     point_t max;
60 } range_t;
61
62 #endif

```

Listing 28: tree\_types.h

### 9.1.3 crew command code

---

```

1 function data = addAgentRepulsiveForce(data)
2 %ADDAGENTREPULSIVEFORCE Summary of this function goes here
3 % Detailed explanation goes here
4
5 % Obstruction effects in case of physical interaction
6
7 % get maximum agent distance for which we calculate force

```

```

r_max = data.r_influence;
9 tree = 0;

11 for fi = 1:data.floor_count
    pos = [arrayfun(@(a) a.p(1), data.floor(fi).agents);
13         arrayfun(@(a) a.p(2), data.floor(fi).agents)];;

15 % update range tree of lower floor
tree_lower = tree;

17 agents_on_floor = length(data.floor(fi).agents);

19 % init range tree of current floor
21 if agents_on_floor > 0
    tree = createRangeTree(pos);
23 end

25 for ai = 1:agents_on_floor
    pi = data.floor(fi).agents(ai).p;
27     vi = data.floor(fi).agents(ai).v;
        ri = data.floor(fi).agents(ai).r;

29     % use range tree to get the indices of all agents near agent ai
31     idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
32                     pi(2) - r_max, pi(2) + r_max)';
33
35     % loop over agents near agent ai
for aj = idx

    % if force has not been calculated yet...
    if aj > ai
        pj = data.floor(fi).agents(aj).p;
        vj = data.floor(fi).agents(aj).v;
        rj = data.floor(fi).agents(aj).r;

43         % vector pointing from j to i
        nij = (pi - pj) * data.meter_per_pixel;

45         % distance of agents
d = norm(nij);

49         % normalized vector pointing from j to i
nij = nij / d;
51         % tangential direction
tij = [-nij(2), nij(1)];

53         % sum of radii
rij = (ri + rj);

55         % repulsive interaction forces

```

```

59         if d < rij
60             T1 = data.k*(rij - d);
61             T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
62         else
63             T1 = 0;
64             T2 = 0;
65         end
66
67         F = (data.A * exp((rij - d)/data.B) + T1)*nij + T2;
68
69         data.floor(fi).agents(ai).f = ...
70             data.floor(fi).agents(ai).f + F;
71         data.floor(fi).agents(aj).f = ...
72             data.floor(fi).agents(aj).f - F;
73     end
74
75 % include agents on stairs!
76 if fi > 1
77     % use range tree to get the indices of all agents near agent ai
78     if ~isempty(data.floor(fi-1).agents)
79         idx = rangeQuery(tree_lower, pi(1) - r_max, ...
80                           pi(1) + r_max, pi(2) - r_max, pi(2) + r_max)';
81
82         % if there are any agents...
83         if ~isempty(idx)
84             for aj = idx
85                 pj = data.floor(fi-1).agents(aj).p;
86                 if data.floor(fi-1).img_stairs_up(round(pj(1)),
87                     round(pj(2)))
88
89                     vj = data.floor(fi-1).agents(aj).v;
90                     rj = data.floor(fi-1).agents(aj).r;
91
92                     % vector pointing from j to i
93                     nij = (pi - pj) * data.meter_per_pixel;
94
95                     % distance of agents
96                     d = norm(nij);
97
98                     % normalized vector pointing from j to i
99                     nij = nij / d;
100                    % tangential direction
101                    tij = [-nij(2), nij(1)];
102
103                    % sum of radii
104                    rij = (ri + rj);
105
106                    % repulsive interaction forces
107                    if d < rij

```

```

107          T1 = data.k*(rij - d);
108          T2 = data.kappa*(rij - d)*dot((vj -
109                                         vi),tij)*tij;
110      else
111          T1 = 0;
112          T2 = 0;
113      end
114
115      F = (data.A * exp((rij - d)/data.B) + T1)*nij
116          + T2;
117
118      data.floor(fi).agents(ai).f = ...
119          data.floor(fi).agents(ai).f + F;
120      data.floor(fi-1).agents(aj).f = ...
121          data.floor(fi-1).agents(aj).f - F;
122
123      end
124  end
125 end

```

Listing 29: addAgentRepulsiveForce.m

```

1 function data = addDesiredForce(data)
%ADDDESIREDFORCE add 'desired' force contribution (towards nearest exit or
3 %staircase)

5 for fi = 1:data.floor_count

7     for ai=1:length(data.floor(fi).agents)

9         % get agent's data
10        p = data.floor(fi).agents(ai).p;
11        m = data.floor(fi).agents(ai).m;
12        v0 = data.floor(fi).agents(ai).v0;
13        v = data.floor(fi).agents(ai).v;

15
16        % get direction towards nearest exit
17        ex = lerp2(data.floor(fi).img_dir_x, p(1), p(2));
18        ey = lerp2(data.floor(fi).img_dir_y, p(1), p(2));
19        e = [ex ey];

21        % get force
22        Fi = m * (v0*e - v)/data.tau;
23
24        % add force
25        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;

```

```
    end  
27 end
```

Listing 30: addDesiredForce.m

```
function data = addWallForce(data)  
2 %ADDWALLFORCE adds wall's force contribution to each agent  
  
4 for fi = 1:data.floor_count  
  
6     for ai=1:length(data.floor(fi).agents)  
        % get agents data  
8         p = data.floor(fi).agents(ai).p;  
         ri = data.floor(fi).agents(ai).r;  
10        vi = data.floor(fi).agents(ai).v;  
  
12        % get direction from nearest wall to agent  
13        nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));  
14        ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));  
  
16        % get distance to nearest wall  
17        diW = lerp2(data.floor(fi).img_wall_dist, p(1), p(2));  
18  
20        % get perpendicular and tangential unit vectors  
21        niW = [ nx ny];  
        tiW = [-ny nx];  
22  
  
24        % calculate force  
25        if diW < ri  
26            T1 = data.k * (ri - diW);  
            T2 = data.kappa * (ri - diW) * dot(vi, tiW) * tiW;  
27        else  
            T1 = 0;  
            T2 = 0;  
        end  
32        Fi = (data.A * exp((ri-diW)/data.B) + T1)*niW - T2;  
  
34        % add force to agent's current force  
35        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;  
36    end  
end
```

Listing 31: addWallForce.m

```
function data = applyForcesAndMove(data)  
2 %APPLYFORCESANDMOVE apply current forces to agents and move them using  
%the timestep and current velocity  
4  
n_velocity_clamps = 0;
```

```

6 % loop over all floors higher than exit floor
8 for fi = data.floor_exit:data.floor_count

10    % init logical arrays to indicate agents that change the floor or exit
11    % the simulation
12    floorchange = false(length(data.floor(fi).agents),1);
13    exited = false(length(data.floor(fi).agents),1);

14    % loop over all agents
15    for ai=1:length(data.floor(fi).agents)
16        % add current force contributions to velocity
17        v = data.floor(fi).agents(ai).v + data.dt * ...
18            data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;

20        % clamp velocity
21        if norm(v) > data.v_max
22            v = v / norm(v) * data.v_max;
23            n_velocity_clamps = n_velocity_clamps + 1;
24        end

26        % get agent's new position
27        newp = data.floor(fi).agents(ai).p + ...
28            v * data.dt / data.meter_per_pixel;

30        % if the new position is inside a wall, remove perpendicular
31        % component of the agent's velocity
32        if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
33            data.floor(fi).agents(ai).r

36            % get agent's position
37            p = data.floor(fi).agents(ai).p;

38            % get wall distance gradient (which is off course perpendicular
39            % to the nearest wall)
40            nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
41            ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
42            n = [nx ny];

44            % project out perpendicular component of velocity vector
45            v = v - dot(n,v)/dot(n,n)*n;

48            % get agent's new position
49            newp = data.floor(fi).agents(ai).p + ...
50                v * data.dt / data.meter_per_pixel;
51        end

52        % check if agents position is ok
53        % repositioning after 50 times clogging
54        % deleting if agent has a NaN position

```

```

56     if ~isnan(newp)
57         if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
58             newp = data.floor(fi).agents(ai).p;
59             v = [0 0];
60             data.floor(fi).agents(ai).clogged =
61                 data.floor(fi).agents(ai).clogged + 1;
62             fprintf('WARNING: clogging agent %i on floor %i (%i).
63                         Position
64                         (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
65             if data.floor(fi).agents(ai).clogged >= 40
66                 nx = rand(1)*2 - 1;
67                 ny = rand(1)*2 - 1;
68                 n = [nx ny];
69                 v = n*data.v_max/2;
70                 fprintf('WARNING: agent %i on floor %i velocity set
71                         random to get out of wall. Position
72                         (%f,%f).\n',ai,fi,newp(1),newp(2))
73
74             % get agent's new position
75             newp = data.floor(fi).agents(ai).p + ...
76                 v * data.dt / data.meter_per_pixel;
77             if isnan(newp)
78                 % get rid of disturbing agent
79                 fprintf('WARNING: position of an agent is NaN!
80                         Deleted this agent.\n')
81                 exited(ai) = 1;
82                 data.agents_exited = data.agents_exited +1;
83                 data.output.deleted_agents=data.output.deleted_agents+1;
84                 newp = [1 1];
85             end
86         end
87     end
88 else
89     % get rid of disturbing agent
90     fprintf('WARNING: position of an agent is NaN! Deleted this
91             agent.\n')
92     exited(ai) = 1;
93     data.agents_exited = data.agents_exited +1;
94     data.output.deleted_agents=data.output.deleted_agents+1;
95     newp = [1 1];
96 end
97
98 % update agent's velocity and position
99 data.floor(fi).agents(ai).v = v;
100 data.floor(fi).agents(ai).p = newp;
101
102 % reset forces for next timestep
103 data.floor(fi).agents(ai).f = [0 0];

```

```

100      % check if agent reached a staircase down and indicate floor change
101      if data.floor(fi).img_stairs_down(round(newp(1)), round(newp(2)))
102          floorchange(ai) = 1;
103      end

104      % check if agent reached an exit
105      if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
106          exited(ai) = 1;
107          data.agents_exited = data.agents_exited +1;
108
109      %
110      fprintf('agent exited from upper loop\n');

111      %save current exit nr
112      data.current_exit = data.exit_nr(round(newp(1)),
113                                      round(newp(2)));

114  %
115
116      %update exit_left
117      data.exit_left(1,data.current_exit) =
118          data.exit_left(1,data.exit_nr(round(newp(1)),
119                         round(newp(2)))) - 1;

120      %close exit if there is no more free space
121      if data.exit_left(1,data.current_exit) < 1

122      %change current exit to wall
123      data.floor(data.floor_exit).img_wall =
124          data.floor(data.floor_exit).img_wall == 1 ...
125              | (data.exit_nr == (data.current_exit));
126      data.floor(data.floor_exit).img_exit =
127          data.floor(data.floor_exit).img_exit == 1 ...
128              & (data.exit_nr ~= (data.current_exit));

129      %redo initEscapeRoutes and initWallForces with new exit
130      and wall parameters
131      data = initEscapeRoutes(data);
132      data = initWallForces(data);

133  %
134      fprintf('new routes from upper loop\n');

135      end
136  end
137
138      % add appropriate agents to next lower floor
139      if fi > data.floor_exit
140          data.floor(fi-1).agents = [data.floor(fi-1).agents
141                                     data.floor(fi).agents(floorchange)];
142      end

```

```

142
143     % delete these and exited agents
144     data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
145 end
146
147
148
149
150
151     % loop over all floors lower than exit floor
152 for fi = 1:data.floor_exit
153
154     % init logical arrays to indicate agents that change the floor or exit
155     % the simulation
156     floorchange = false(length(data.floor(fi).agents),1);
157     exited = false(length(data.floor(fi).agents),1);
158
159     % loop over all agents
160     for ai=1:length(data.floor(fi).agents)
161         % add current force contributions to velocity
162         v = data.floor(fi).agents(ai).v + data.dt * ...
163             data.floor(fi).agents(ai).f / data.floor(fi).agents(ai).m;
164
165         % clamp velocity
166         if norm(v) > data.v_max
167             v = v / norm(v) * data.v_max;
168             n_velocity_clamps = n_velocity_clamps + 1;
169         end
170
171         % get agent's new position
172         newp = data.floor(fi).agents(ai).p + ...
173             v * data.dt / data.meter_per_pixel;
174
175         % if the new position is inside a wall, remove perpendicular
176         % component of the agent's velocity
177         if lerp2(data.floor(fi).img_wall_dist, newp(1), newp(2)) < ...
178             data.floor(fi).agents(ai).r
179
180             % get agent's position
181             p = data.floor(fi).agents(ai).p;
182
183             % get wall distance gradient (which is of course perpendicular
184             % to the nearest wall)
185             nx = lerp2(data.floor(fi).img_wall_dist_grad_x, p(1), p(2));
186             ny = lerp2(data.floor(fi).img_wall_dist_grad_y, p(1), p(2));
187             n = [nx ny];
188
189             % project out perpendicular component of velocity vector
190             v = v - dot(n,v)/dot(n,n)*n;

```

```

192         % get agent's new position
193         newp = data.floor(fi).agents(ai).p + ...
194             v * data.dt / data.meter_per_pixel;
195     end
196
197
198     % check if agents position is ok
199     % repositioning after 50 times clogging
200     % deleting if agent has a NaN position
201     if ~isnan(newp)
202         if data.floor(fi).img_wall(round(newp(1)), round(newp(2)))
203             newp = data.floor(fi).agents(ai).p;
204             v = [0 0];
205             data.floor(fi).agents(ai).clogged =
206                 data.floor(fi).agents(ai).clogged + 1;
207             fprintf('WARNING: clogging agent %i on floor %i (%i).
208                 Position
209                 (%f,%f).\n',ai,fi,data.floor(fi).agents(ai).clogged,newp(1),newp(2))
210             if data.floor(fi).agents(ai).clogged >= 40
211                 nx = rand(1)*2 - 1;
212                 ny = rand(1)*2 - 1;
213                 n = [nx ny];
214                 v = n*data.v_max/2;
215                 fprintf('WARNING: agent %i on floor %i velocity set
216                     random to get out of wall. Position
217                     (%f,%f).\n',ai,fi,newp(1),newp(2))
218
219
220         % get agent's new position
221         newp = data.floor(fi).agents(ai).p + ...
222             v * data.dt / data.meter_per_pixel;
223         if isnan(newp)
224             % get rid of disturbing agent
225             fprintf('WARNING: position of an agent is NaN!
226                 Deleted this agent.\n')
227             exited(ai) = 1;
228             data.agents_exited = data.agents_exited +1;
229             data.output.deleted_agents=data.output.deleted_agents+1;
230             newp = [1 1];
231         end
232     end
233 else
234     % get rid of disturbing agent
235     fprintf('WARNING: position of an agent is NaN! Deleted this
236         agent.\n')
237     exited(ai) = 1;
238     data.agents_exited = data.agents_exited +1;
239     data.output.deleted_agents=data.output.deleted_agents+1;
240     newp = [1 1];
241 end

```

```

236     % update agent's velocity and position
238     data.floor(fi).agents(ai).v = v;
239     data.floor(fi).agents(ai).p = newp;

240     % reset forces for next timestep
241     data.floor(fi).agents(ai).f = [0 0];

242     % check if agent reached a staircase up and indicate floor change
243     if data.floor(fi).img_stairs_up(round(newp(1)), round(newp(2)))
244         floorchange(ai) = 1;
245     end

246     % check if agent reached an exit
247     if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
248         exited(ai) = 1;
249         data.agents_exited = data.agents_exited +1;
250     end

251     %
252     fprintf('agent exited from lower loop\n');

253     %save current exit nr
254     data.current_exit = data.exit_nr(round(newp(1)),
255                                     round(newp(2)));

256     %update exit_left
257     data.exit_left(1,data.current_exit) =
258         data.exit_left(1,data.exit_nr(round(newp(1)),
259                         round(newp(2)))) - 1;

259     %close exit if there is no more free space
260     if data.exit_left(1,data.current_exit) < 1

261         %change current exit to wall
262         data.floor(data.floor_exit).img_wall =
263             data.floor(data.floor_exit).img_wall == 1 ...
264             | (data.exit_nr == (data.current_exit));
265         data.floor(data.floor_exit).img_exit =
266             data.floor(data.floor_exit).img_exit == 1 ...
267             & (data.exit_nr ~= (data.current_exit));

268         %redo initEscapeRoutes and initWallForces with new exit
269         % and wall parameters
270         data = initEscapeRoutes(data);
271         data = initWallForces(data);

272         %
273         fprintf('new routes from lower loop\n');

274     end

275     end

```

```

    end
280
% add appropriate agents to next lower floor
282 if fi < data.floor_exit
    data.floor(fi+1).agents = [data.floor(fi+1).agents ...
284                                     data.floor(fi).agents(floorchange)];
end
286
% delete these and exited agents
288 data.floor(fi).agents = data.floor(fi).agents(~(floorchange|exited));
end
290
if data.switch_done==0 && data.step ~=1 &&
    data.open_on_x_agents_on_boat>sum(data.output.agents_per_floor(:,data.step-1))
292     data.floor(data.floor_exit).img_exit =
        data.floor(data.floor_exit).img_exit_second;
    data.floor(data.floor_exit).img_wall =
        data.floor(data.floor_exit).img_wall_second;
294     data = initEscapeRoutes(data);
    data = initWallForces(data);
    data.switch_done=1;
    fprintf('ALL BOATS ARE OPEN NOW FOR EVACUATION! Opened on time
            %i\n',data.step*data.dt)
298 end
300 % if n_velocity_clamps > 0
%     fprintf(['WARNING: clamped velocity of %d agents, ...
302 %             \'possible simulation instability.\n'], n_velocity_clamps);
% end

```

Listing 32: applyForcesAndMove.m

```

1 function val = checkForIntersection(data, floor_idx, agent_idx)
% check an agent for an intersection with another agent or a wall
3 % the check is kept as simple as possible
%
5 % arguments:
%   data           global data structure
7 %   floor_idx      which floor to check
%   agent_idx      which agent on that floor
9 %   agent_new_pos  vector: [x,y], desired agent position to check
%
11 % return:
%   0             for no intersection
13 %   1             has an intersection with wall
%   2             with another agent
15
val = 0;
17
p = data.floor(floor_idx).agents(agent_idx).p;

```

```

19 r = data.floor(floor_idx).agents(agent_idx).r;

21 % check for agent intersection
22 for i=1:length(data.floor(floor_idx).agents)
23     if i~=agent_idx
24         if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
25             ...
26                 <= r + data.floor(floor_idx).agents(i).r
27                 val=2;
28                 return;
29         end
30     end
31 end

33 % check for wall intersection
34 if lerp2(data.floor(floor_idx).img_wall_dist, p(1), p(2)) < r
35     val = 1;
36 end

```

Listing 33: checkForIntersection.m

---

```

1 mex 'fastSweeping.c'
2 mex 'getNormalizedGradient.c'
3 mex 'lerp2.c'
4 mex 'createRangeTree.c'
5 mex 'rangeQuery.c'

```

---

Listing 34: compileC.m

---

```

1 function data = initAgents(data)

3 % place agents randomly in desired spots, without overlapping
4

7 function radius = getAgentRadius()
8     %radius of an agent in meters
9     radius = data.r_min + (data.r_max-data.r_min)*rand();
10 end

11 data.agents_exited = 0; %how many agents have reached the exit
12 data.total_agent_count = 0;

15 floors_with_agents = 0;
16 agent_count = data.agents_per_floor;
17 for i=1:data.floor_count
18     data.floor(i).agents = [];
19     [y,x] = find(data.floor(i).img_spawn);

```

---

```

21     if ~isempty(x)
22         floors_with_agents = floors_with_agents + 1;
23         for j=1:agent_count
24             cur_agent = length(data.floor(i).agents) + 1;
25
26             % init agent
27             data.floor(i).agents(cur_agent).r = getAgentRadius();
28             data.floor(i).agents(cur_agent).v = [0, 0];
29             data.floor(i).agents(cur_agent).f = [0, 0];
30             data.floor(i).agents(cur_agent).m = data.m;
31             data.floor(i).agents(cur_agent).v0 = data.v0;
32             data.floor(i).agents(cur_agent).clogged = 0; %to check if
33                 agent is hanging in the wall
34
35             tries = 10;
36             while tries > 0
37                 % randomly pick a spot and check if it's free
38                 idx = randi(length(x));
39                 data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
40                 if checkForIntersection(data, i, cur_agent) == 0
41                     tries = -1; % leave the loop
42                 end
43                 tries = tries - 1;
44             end
45             if tries > -1
46                 %remove the last agent
47                 data.floor(i).agents = data.floor(i).agents(1:end-1);
48             end
49         end
50         data.total_agent_count = data.total_agent_count +
51             length(data.floor(i).agents);
52
53         if length(data.floor(i).agents) ~= agent_count
54             fprintf(['WARNING: could only place %d agents on floor %d ' ...
55                     'instead of the desired %d.\n'], ...
56                     length(data.floor(i).agents), i, agent_count);
57         end
58     end
59     if floors_with_agents==0
60         error('no spots to place agents!');
61     end

```

Listing 35: initAgents.m

---

```

function data = initEscapeRoutes(data)
%INITESCAPEROUTES Summary of this function goes here
%   Detailed explanation goes here

```

```

4   for i=1:data.floor_count
6       boundary_data = zeros(size(data.floor(i).img_wall));
8       boundary_data(data.floor(i).img_wall) = 1;
10      if i<data.floor_exit
11          boundary_data(data.floor(i).img_stairs_up) = -1;
12      elseif i>data.floor_exit
13          boundary_data(data.floor(i).img_stairs_down) = -1;
14      else
15          boundary_data(data.floor(i).img_exit) = -1;
16      end
17      exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
18      [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
19          getNormalizedGradient(boundary_data, -exit_dist);
20  end

```

Listing 36: initEscapeRoutes.m

---

```

function data = initialize(config)
% initialize the internal data from the config data
%
4 % arguments:
% config      data structure from loadConfig()
6 %
% return:
8 % data       data structure: all internal data used for the main loop
%
10 %           all internal data is stored in pixels NOT in meters

12 data = config;
14 %
%for convenience
16 data.pixel_per_meter = 1/data.meter_per_pixel;

18 fprintf('Init escape routes...\n');
data = initEscapeRoutes(data);
20 fprintf('Init wall forces...\n');
data = initWallForces(data);
22 fprintf('Init agents...\n');
data = initAgents(data);
24 %
% maximum influence of agents on each other
26 data.r_influence = data.pixel_per_meter * ...

```

```

28     fzero(@(r) data.A * exp((2*data.r_max-r)/data.B) - 1e-4, data.r_max);

30 fprintf('Init plots...\n');
%init the plots
32 %exit plot
    data.figure_exit=figure;
34 hold on;
    axis([0 data.duration 0 data.total_agent_count]);
36 title(sprintf('agents that reached the exit (total agents: %i)', data.total_agent_count));

38 % floors plot
    data.figure_floors=figure;
40 % figure('units','normalized','outerposition',[0 0 1 1])
    data.figure_floors_subplots_w = data.floor_count;
42 data.figure_floors_subplots_h = 4;
    for i=1:config.floor_count
        data.floor(i).agents_on_floor_plot =
            subplot(data.figure_floors_subplots_h,
                    data.figure_floors_subplots_w, 3*data.floor_count - i+1 +
                    data.figure_floors_subplots_w);
        if i == config.floor_exit - 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(2*config.floor_count+1):3*config.floor_count]);
        elseif i == config.floor_exit
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w,
                        [(config.floor_count+1):2*config.floor_count]);
        elseif i == config.floor_exit + 1
            data.floor(i).building_plot =
                subplot(data.figure_floors_subplots_h,
                        data.figure_floors_subplots_w, [1:config.floor_count]);
        end
52 end

54 % init output matrizes
    data.output = struct;
56 data.output.config = config;
    data.output.agents_per_floor =
        ones(data.floor_count,data.duration/data.dt).*(-1);
58 data.output.exit_left = zeros(data.exit_count,data.duration/data.dt);

60 % prepare output file name
    data.output_file_name = ['output_' data.frame_basename];
62 % prepare video file name
64 data.video_file_name = ['video_' data.frame_basename '.avi'];

```

```

66 % set deleted_agents to zero
data.output.deleted_agents = 0;

```

Listing 37: initialize.m

```

function data = initWallForces(data)
%INITWALLFORCES init wall distance maps and gradient maps for each floor

for i=1:data.floor_count

    % init boundary data for fast sweeping method
    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) = -1;

    % get wall distance
    wall_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    data.floor(i).img_wall_dist = wall_dist;

    % get normalized wall distance gradient
    [data.floor(i).img_wall_dist_grad_x, ...
     data.floor(i).img_wall_dist_grad_y] = ...
        getNormalizedGradient(boundary_data, wall_dist-data.meter_per_pixel);
end

```

Listing 38: initWallForces.m

```

1 function config = loadConfig(config_file)
% load the configuration file
3 %
% arguments:
5 % config_file      string, which configuration file to load
%
7

9 % get the path from the config file -> to read the images
config_path = fileparts(config_file);
11 if strcmp(config_path, '') == 1
    config_path = '.';
end

15 fid = fopen(config_file);
input = textscan(fid, '%s=%s');
fclose(fid);

19 keynames = input{1};
values = input{2};
21
%convert numerical values from string to double
23 v = str2double(values);

```

```

    idx = ~isnan(v);
25 values(idx) = num2cell(v(idx));

27 config = cell2struct(values, keynames);

29
% read the images
31 for i=1:config.floor_count

33     %building structure
34     file = config.(sprintf('floor_%d_build', i));
35     file_name = [config_path '/' file];
36     img_build = imread(file_name);

37     % decode images
38     config.floor(i).img_wall = (img_build(:, :, 1) == 0 ...
39                                 & img_build(:, :, 2) == 0 ...
40                                 & img_build(:, :, 3) == 0);

43     config.floor(i).img_spawn = (img_build(:, :, 1) == 255 ...
44                                 & img_build(:, :, 2) == 0 ...
45                                 & img_build(:, :, 3) == 255);

47 %second possibility:
48 %pixel is exit if 1-->0, 3-->0, and if 2 is between 255 and 230 or if no
49 %red or blue

51     config.floor(i).img_exit = (img_build(:, :, 1) == 0 ...
52                                 & img_build(:, :, 2) ~= 0 ...
53                                 & img_build(:, :, 3) == 0);

55
56     config.floor(i).img_stairs_up = (img_build(:, :, 1) == 255 ...
57                                     & img_build(:, :, 2) == 0 ...
58                                     & img_build(:, :, 3) == 0);

59     config.floor(i).img_stairs_down = (img_build(:, :, 1) == 0 ...
60                                     & img_build(:, :, 2) == 0 ...
61                                     & img_build(:, :, 3) == 255);

63

65     if i == config.floor_exit

66         %make the exit_nr matrix where the number of exit is indicated in
67             %each
68             %pixel
69
70         %make a zeroes matrix as big as img_exit
71         config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

```

```

73     %make a zeros vector as long as floor_exit
74     config.exit_left = zeros(1,config.exit_count);

75     %loop over all exits
76     for e=1:config.exit_count

77         %build the exit_nr matrix
78         config.exit_nr = config.exit_nr + e*( img_build(:, :, 1) == 0
79             & img_build(:, :, 2) == (256-e) & img_build(:, :, 3) == 0 );
80         ;

81         %build the exit_left matrix
82         config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));

83     end
84
85 end

86
87 %init the plot image here, because this won't change
88 config.floor(i).img_plot = 5*config.floor(i).img_wall ...
89     + 4*config.floor(i).img_stairs_up ...
90     + 3*config.floor(i).img_stairs_down ...
91     + 2*config.floor(i).img_exit ...
92     + 1*config.floor(i).img_spawn;
93 config.color_map = [1 1 1; 0.9 0.9 0.9; 0 1 0; 0.4 0.4 1; 1 0.4 0.4; 0
94     0 0];
95 end

96
97

98 % build open_second matrix
99 for i=1:config.open_second_nr
100    config.open_second(i)=config.(sprintf('open_second_%i', i));
101 end

102
103 % save the "all exits open" configuration
104 config.floor(config.floor_exit).img_exit_second =
105     config.floor(config.floor_exit).img_exit;
106 config.floor(config.floor_exit).img_wall_second =
107     config.floor(config.floor_exit).img_wall;

108
109 % replace the open_second exits in img_exit with a wall
110 for i=1:config.open_second_nr
111    config.floor(config.floor_exit).img_wall(find(config.exit_nr ==
112        config.open_second(i))) = 1;
113    config.floor(config.floor_exit).img_exit(find(config.exit_nr ==
114        config.open_second(i))) = 0;
115 end

116
117 % set the boolean to check if switch from first to second mode has already
118 % been executed

```

```
config.switch_done = 0;
```

Listing 39: loadConfig.m

```
function plotAgentsPerFloor(data, floor_idx)
%plot time vs agents on floor

h = subplot(data.floor(floor_idx).agents_on_floor_plot);

set(h, 'position',[0.05+(data.floor_count -
    floor_idx)/(data.figure_floors_subplots_w+0.2), ...
    0.05, 1/(data.figure_floors_subplots_w*1.2), 0.3-0.05 ]);

if floor_idx~=data.floor_count
    set(h,'ytick',[]) %hide y-axis label
end

axis([0 data.time+data.dt 0 data.agents_per_floor*2]);
%axis([0 data.duration 0 data.agents_per_floor*2]);

hold on;
plot(data.time, length(data.floor(floor_idx).agents), 'b-');
hold off;

title(sprintf('%i', floor_idx));
```

Listing 40: plotAgentsPerFloor.m

```
function plotExitedAgents(data)
%plot time vs exited agents

hold on;
plot(data.time, data.agents_exited, 'r-');
hold off;
```

Listing 41: plotExitedAgents.m

```
function plotFloor(data, floor_idx)
if floor_idx == data.floor_exit-1 || floor_idx == data.floor_exit ||
    floor_idx == data.floor_exit+1
    h=subplot(data.floor(floor_idx).building_plot);

set(h,
    'position',[0,0.35+0.65/3*(floor_idx-data.floor_exit+1),1,0.65/3-0.005]);

hold off;
% the building image
imagesc(data.floor(floor_idx).img_plot);
```

```

    hold on;
12
    %plot options
14 colormap(data.color_map);
    axis equal;
16 axis manual; %do not change axis on window resize

18 set(h, 'Visible', 'off')
    % title(sprintf('floor %i', floor_idx))
20
    % plot agents
22 if ~isempty(data.floor(floor_idx).agents)
        ang = [linspace(0,2*pi, 10) nan];
24     rmul = [cos(ang) sin(ang)] * data.pixel_per_meter;
        draw = cell2mat(arrayfun(@(a) repmat(a.p,length(ang),1) + a.r*rmul, ...
26         data.floor(floor_idx).agents, 'UniformOutput', false));
        line(draw(:,2), draw(:,1), 'Color', 'r');
28 end

30 hold off;
end
32 end

```

---

Listing 42: plotFloor.m

```

function simulate(config_file)
% run this to start the simulation

4 % start recording the matlab output window for debugging reasons
diary log
6
if nargin==0
    config_file='../../data/config1.conf';
end
10
fprintf('Load config file...\n');
12 config = loadConfig(config_file);

14 data = initialize(config);

16 data.step = 1;
data.time = 0;
18 fprintf('Start simulation...\n');

20 % tic until simulation end
simstart = tic;
22
%make video while simulation
24 if data.save_frames==1
    vidObj=VideoWriter(data.video_file_name);

```

```

26         open(vidObj);
27     end
28
29     while (data.time < data.duration)
30         % tic until timestep end
31         tstart=tic;
32         data = addDesiredForce(data);
33         data = addWallForce(data);
34         data = addAgentRepulsiveForce(data);
35         data = applyForcesAndMove(data);
36
37         % dump agents_per_floor to output
38         for floor=1:data.floor_count
39             data.output.agents_per_floor(floor,data.step) =
40                 length(data.floor(floor).agents);
41         end
42
43         % dump exit_left to output
44         data.output.exit_left(:,data.step) = data.exit_left';
45
46         if mod(data.step,data.save_step) == 0
47
48             % do the plotting
49             set(0,'CurrentFigure',data.figure_floors);
50             for floor=1:data.floor_count
51                 plotAgentsPerFloor(data, floor);
52                 plotFloor(data, floor);
53             end
54
55             if data.save_frames==1
56                 %
57                 print('-depsc2',sprintf('frames/%s_%04i.eps', ...
58                 data.frame_basename,data.step), data.figure_floors);
59
60             %
61             make video while simulate
62             currFrame=getframe(data.figure_floors);
63             writeVideo(vidObj,currFrame);
64
65             end
66
67             set(0,'CurrentFigure',data.figure_exit);
68             plotExitedAgents(data);
69
70             if data.agents_exited == data.total_agent_count
71                 fprintf('All agents are now saved (or are they?). Time: %.2f
72                     sec\n', data.time);
73                 fprintf('Total Agents: %i\n', data.total_agent_count);
74
75                 print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
76                     data.frame_basename), data.figure_floors);
77                 break;

```

```

74     end

76     % toc of timestep
77     data.telapsed = toc(tstart);
78     % toc of whole simulation
79     data.output.simulation_time = toc(simstart);

80     % save output
81     output = data.output;
82     save(data.output_file_name,'output')
83     fprintf('Frame %i done (took %.3fs; %.3fs out of %.3gs
84             simulated).\n', data.step, data.telapsed, data.time,
85             data.duration);

86 end

87 % update step
88 data.step = data.step+1;

89 % update time
90 if (data.time + data.dt > data.duration)
91     data.dt = data.duration - data.time;
92     data.time = data.duration;
93 else
94     data.time = data.time + data.dt;
95 end

96
97 end

98 %make video while simulation
99 close(vidObj);

100 % toc of whole simulation
101 data.output.simulation_time = toc(simstart);

102 % save complete simulation
103 output = data.output;
104 save('output','output')
105 fprintf('Simulation done in %i seconds and saved data to output file.\n',
106         data.output.simulation_time);

107 % save diary
108 diary

```

Listing 43: simulate.m