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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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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I hereby declare that the written work I have submitted entitled

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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Contents

1 Abstract

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 implenting the computer code. Whereas Andreas and Fabian concentrated on providing background information, compared the results with the reality and doing its verification.

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 safe 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 reproduction, 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 PC based evacuation and pedestrian dynamics model that is capable of simulating individual people, behaviour 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 and 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 practised 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 localised 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?

If we have time to spare we analyse 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?

4 Description of the Model

We will base the modeling part 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 c with a MATLAB surface to rapidly simulate the evacuation of multi-level buildings.

4.1 Social Force Model

The simulation is based on the social force model for pedestrian dynamics introduced by Dirk Helbling and Peter Molnar [1]. The general idea is that a pedestrian can be represented by a particle of a certain mass. Depending on the specific problem, there are defined forces acting on this particle. Due to these forces the particle moves with a certain speed and velocity in a defined direction. In our model the following forces are acting on an agent:

- f_D, pulls the agent into the desired direction
- f_{ij} repulsive forces, keeps a certain distance between agent i and agent j
- f_{iW} wall force, prevents agents i from running into walls

For each timestep in the simulation, the forces acting on agent i are calculated. Knowing the forces, we can calculate the change in velocity at this timestep:

$$m_i \frac{\mathsf{d}\mathbf{v}_i}{\mathsf{d}t} = m_i f_D + \sum_{j(\neq i)} f_{ij} + \sum_{W} f_{iW} \tag{1}$$

Finally, knowing the change in position the new position can be calculatet:

$$\mathbf{r}_{i,new} = \mathbf{r}_{i,previous} + \mathbf{v}_i \mathbf{dt} \tag{2}$$

For more detailed information about the forces and their implementation please refer to [2]chapter 4.

4.2 General Model

Similar to the building we necessarily need an implementation of a common ship shape [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 and shape
- Area used by specific rooms (coaches for passengers, lounge area, corridors)

Our target is to decrease the evacuation time. Measurements will be made on the time to evacuate:

- 10%
- 50%
- 90%
- 99% of all passengers.

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

- Disposition of the specific room types (e.g. changing the geometry of the corridors without changing the total area used for corridors)
- 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?)

4.3 Force Model

5 Implementation

5.1 Code

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

5.1.1 Code adjustment - Exits

<u>Reason:</u>
The first change which was necessary was due to the fact that the exits in our simulation are not simply on the lowest floor.
<u>Assumption:</u>
In the case of an emergancy all agents are keen to leave the ship as fast as possible. Therefore in our simulation all passangers above the exits floor are only enabled to move down and passengers lower than the exit floor move upstairs.
<u>Function:</u>
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 by splitting the loop, in which we calculate the forces and moves of the agents, in two parts. First we loop over all floors higher than the exit floor in which the agents only are allowed to move down or take an exit. Secondly we do the same for all people in the floors lower than the exit floor where the passengers only can move up or take an exit.
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. Means for each agent there is one number set: If the agent reaches a staircase and therefore changes the floor he is a 1 otherwise he is a 0. The assumption also is a great simplification for the pictures since we do not have to mess with the problem of having overlapping stairs.

5.1.2 Code adjustment - Different exits

Reason:
Because the exits model rescueboats, which can only hold a limited number of agents, we were forced to find a way how to differ the exits from each other and to assign a specific number to every exit.
Function:
loadConfig.m
New variables:
- *Exit_count*, to define the number of exit.
- For each exit k: *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:
We had to make some changes in the decoding of the pictures. 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 exits, to be able to distinguish them during the simulation.By defining every pixel which is red to value=0, blue value=0 and green value unequal to zero, we can define a lot of different colored exits by using green values from 256 to 256-*exit_count*.
We implemented the matrix *exit_nr* similar to the already existing one *imgexit*, in which we store a count to number the different exits. The number is defined by the green value of the pixel we are at.

```
%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

5.1.3 Code adjustment - 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 (defined by his number).

```
%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
config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e)); save the number of agents the
exit can hold
end
```

Figure 2: Implementation of the exit_left matrix

In the loop where the forces are calculated and the agents moved, (in function

apllyForcesandMove.m) we added a piece of code, which updates the exit_left matrix at every time-step.
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.

```
%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

If the allowed number of agents exited the number is 0. Now we have 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

5.1.4 Code adjustment - Controlled evacuation

Reason:
With the goal of a faster evacuation, we tried to control the agents to go to specific

exits.
Assumption:
We realised that the biggest problem-zones are the stairs. So, in order to get the agents as fast as possible away from the stairs, once they changed the floor, we decided to split the agents in two groups. One group only reaches one half of the exits and the other group for the others.
Function:
init_agents.m, addDesiredForce.m, initEscapeRoutes_even.m, initEscapeRoutes_odd.m, addDesiredForce.m, initialize.m, initAgents.m, loadConfig.m
New variables:
- *numbr*, each agents gets a number (0 or 1, selected randomly)
- *control_exit*, in the config file you can decide whether or not you want to have controlled exits during your simulation
Modifications:
Essentially, we had to modify the calculation of the force dragging a specific agent to the nearest exit. Therefore we wrote two new functions to init the escape routes.
- initEscapeRoutes_even.m, this function only considers the exits which are identified by an even number.

```
temp1=double(mod(data.exit_nr,2)); %matrix in which every number which is even turns to zero, odd turns to one
temp2=logical((data.floor(i).img_exit)-(temp1));
boundary_data(temp2)=-1; %boundary_data considers only the exits with even numbers −− > -1
```

Figure 6: Implementation to init escape routes for even numbers

→ initEscapeRoutes_.m, this function only considers the exits which are identified by an odd number

```
temp=logical(mod(data.exit_nr,2)); %matrix in which every number which is even turns to zero, odd turns to one
boundary_data(temp)=-1; %boundary_data considers only the exits with odd numbers
```

Figure 7: Implementation to init escape routes for odd numbers

This as a basis we got two different directions to the next exit.

```
→[data.floor(i).img_dir_x_odd, data.floor(i).img_dir_y_odd]
→[data.floor(i).img_dir_x_even, data.floor(i).img_dir_y_even]
```

Figure 8: Functions used to get the forces which drag the agents to the nearest exit

The agents are splitted in even-agents and odd-agents defined by the randomly added number (0 or 1).

```
%even agents
if numbr==0;
%get direction towards nearest exit
ex = lerp2(data.floor(fi).img_dir_x_even, p(1), p(2));
ey = lerp2(data.floor(fi).img_dir_y_even, p(1), p(2));
e = [ex ey];
%get force
Fi = m * (v0*e - v)/data.tau;
% add force
data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
end
```

Figure 9: Implementation to randomly split agents to even and odd

5.2 Ship Decks

6 Simulation Results and Discussion

6.1 Expected Results

- 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 alinging 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 [5] we hope to see some real evacuation dynamics in this system and therefore make conclusion on the fundamental questions.

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%	99%
evacuation time	69s	272s	468s	614s

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:

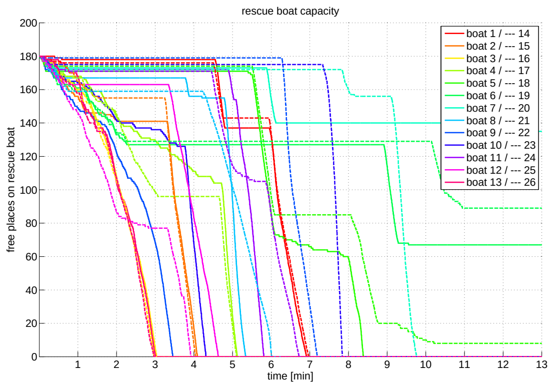

Figure 10: Standard simulation: Boat capacities during simulation

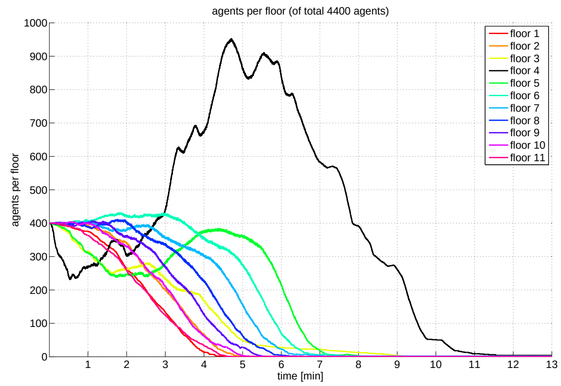

Figure 11: Standard simulation: Number of agents per floor

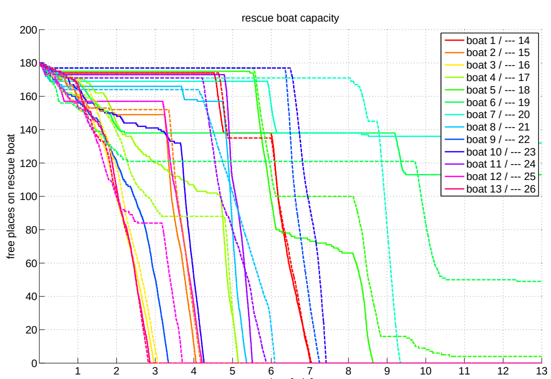

Figure 12: Added stairs simulation: Boat capacities during simulation

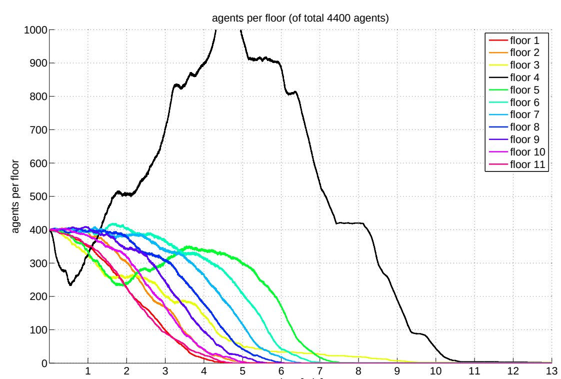

Figure 13: Added stairs simulation: Number of agents per floor

percentage of agents.	10%	50%	90%	99%
evacuation time	72s	259s	461s	595s

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

6.2.3 Modified rescueboat size

As we could see in the simulations with the standard ship, the rescueboats 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 the lifeboats near to 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%	99%
evacuation time	71.44s	257.12s	419.4s	571.4s

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

6.2.4 Controlled outputs

6.2.5 Crew command

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 almost 20 seconds. Further 50% of all agents entered the exits approximately 13 seconds earlier compared to the stanard model. In contrast to that the rescueboat capacity utilisation remains basically the same. Another point which was actually not important for our research is that you get a much higher agent densitiy on the exit floor.

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 second half of the evacuation. The last 10% of agents are evacuated 48.6 seconds faster and the last 1% even 42.6 seconds faster. 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 - Controlles outputs

6.3.4 Standard - Crew command

6.4 Discussion

7 Summary and Outlook

7.1 Summary

7.2 Outlook

During our work on this project, we saw a lot of possibilites to improve the model.The target of an ongoing project could be to make the model more realistic. There are a lot of possibilites to achieve this goal.
Some suggestions:

8 References

References

[1] Helbing, Dirk (1995): Social Force Model for Pedestrians Dynamics.

[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

[4] SHIP EVACUATION: http://www.shipevacuation.com/

[5] CRUISE DECK PLANS PUBLIC SITE: http://www.cruisedeckplans.com/DP/Main/decks.php?ship=Costa%20Serena

[6] University of Greenwich (2011): maritimeEXODUS. http://fseg.gre.ac.uk/fire/marine_evac_model.html

[7] Haverie of Costa Concordia (2012): http://de.wikipedia.org/wiki/Costa_Concordia#Havarie_2012

9 Appendix

9.1 Code

9.1.1 *standard* code

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

% Obstruction effects in case of physical interaction

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

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

    % update range tree of lower floor
    tree_lower = tree;

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

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

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

        % use range tree to get the indices of all agents near agent ai
        idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
                                   pi(2) - r_max, pi(2) + r_max)';

        % 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;

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

                % distance of agents
                d = norm(nij);

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

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

                % repulsive interaction forces
                if d < rij
                   T1 = data.k*(rij - d);
                   T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
                else
                   T1 = 0;
                   T2 = 0;
                end

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

                data.floor(fi).agents(ai).f = ...
                    data.floor(fi).agents(ai).f + F;
                data.floor(fi).agents(aj).f = ...
                    data.floor(fi).agents(aj).f - F;
            end
        end
```

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

                % if there are any agents...
                if ~isempty(idx)
                    for aj = idx
                        pj = data.floor(fi-1).agents(aj).p;
                        if data.floor(fi-1).img_stairs_up(round(pj(1)),
                            round(pj(2)))

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

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

                            % distance of agents
                            d = norm(nij);

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

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

                            % repulsive interaction forces
                            if d < rij
                               T1 = data.k*(rij - d);
                               T2 = data.kappa*(rij - d)*dot((vj -
                                   vi),tij)*tij;
                            else
                               T1 = 0;
                               T2 = 0;
                            end

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

                            data.floor(fi).agents(ai).f = ...
                                data.floor(fi).agents(ai).f + F;
                            data.floor(fi-1).agents(aj).f = ...
                                data.floor(fi-1).agents(aj).f - F;
                        end
```

```
                    end
                end
            end
        end
    end
end
```

Listing 1: addAgentRepulsiveForce.m

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

for fi = 1:data.floor_count

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

        % get agent's data
        p = data.floor(fi).agents(ai).p;
        m = data.floor(fi).agents(ai).m;
        v0 = data.floor(fi).agents(ai).v0;
        v = data.floor(fi).agents(ai).v;


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

        % get force
        Fi = m * (v0*e - v)/data.tau;

        % add force
        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
    end
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;

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

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

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

        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
               data.floor(fi).agents(ai).clogged =
                   data.floor(fi).agents(ai).clogged + 1;
               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))
               if data.floor(fi).agents(ai).clogged >= 40
                    nx = rand(1)*2 - 1;
                    ny = rand(1)*2 - 1;
                    n = [nx ny];
                    v = n*data.v_max/2;
                    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))

                    % get agent's new position
                    newp = data.floor(fi).agents(ai).p + ...
                    v * data.dt / data.meter_per_pixel;
                    if isnan(newp)
                        % get rid of disturbing agent
                        fprintf('WARNING: position of an agent is NaN!
                            Deleted this agent.\n')
                        exited(ai) = 1;
                        data.agents_exited = data.agents_exited +1;
                        data.output.deleted_agents=data.output.deleted_agents+1;
                        newp = [1 1];
                    end
                end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this
                agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end


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

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

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

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

%              fprintf('agent exited from upper loop\n');

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

```
%             fprintf(int2str(data.current_exit));

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

            %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));

                %redo initEscapeRoutes and initWallForces with new exit
                    and wall parameters
                data = initEscapeRoutes(data);
                data = initWallForces(data);

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

            end
        end
    end

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

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




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

    % 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 of 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];

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

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


        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
                data.floor(fi).agents(ai).clogged =
                    data.floor(fi).agents(ai).clogged + 1;
```

```
                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))
                if data.floor(fi).agents(ai).clogged >= 40
                     nx = rand(1)*2 - 1;
                     ny = rand(1)*2 - 1;
                     n = [nx ny];
                     v = n*data.v_max/2;
                     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))

                    % get agent's new position
                    newp = data.floor(fi).agents(ai).p + ...
                    v * data.dt / data.meter_per_pixel;
                    if isnan(newp)
                         % get rid of disturbing agent
                         fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
                         exited(ai) = 1;
                         data.agents_exited = data.agents_exited +1;
                         data.output.deleted_agents=data.output.deleted_agents+1;
                         newp = [1 1];
                    end
                end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end

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

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

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

        % check if agent reached an exit
        if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
```

```
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;

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

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

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

                        %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));

                %redo initEscapeRoutes and initWallForces with new exit
                    and wall parameters
                data = initEscapeRoutes(data);
                data = initWallForces(data);

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

            end

        end
    end

    % add appropriate agents to next lower floor
    if fi < data.floor_exit
        data.floor(fi+1).agents = [data.floor(fi+1).agents ...
                                   data.floor(fi).agents(floorchange)];
    end

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

% if n_velocity_clamps > 0
%     fprintf(['WARNING: clamped velocity of %d agents, ' ...
%             'possible simulation instability.\n'], n_velocity_clamps);
```

```
% 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

val = 0;

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

% check for agent intersection
for i=1:length(data.floor(floor_idx).agents)
    if i~=agent_idx
        if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
            ...
                <= r +  data.floor(floor_idx).agents(i).r
            val=2;
            return;
        end
    end
end


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

Listing 5: checkForIntersection.m

```
mex 'fastSweeping.c'
mex 'getNormalizedGradient.c'
mex 'lerp2.c'
mex 'createRangeTree.c'
mex 'rangeQuery.c'
```

Listing 6: compileC.m

```
function data = initAgents(data)

% place agents randomly in desired spots, without overlapping



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

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

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

    if ~isempty(x)
        floors_with_agents = floors_with_agents + 1;
        for j=1:agent_count
            cur_agent = length(data.floor(i).agents) + 1;

            % init agent
            data.floor(i).agents(cur_agent).r = getAgentRadius();
            data.floor(i).agents(cur_agent).v = [0, 0];
            data.floor(i).agents(cur_agent).f = [0, 0];
            data.floor(i).agents(cur_agent).m = data.m;
            data.floor(i).agents(cur_agent).v0 = data.v0;
            data.floor(i).agents(cur_agent).clogged = 0; %to check if
                agent is hanging in the wall

            tries = 10;
            while tries > 0
                % randomly pick a spot and check if it's free
                idx = randi(length(x));
                data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
                if checkForIntersection(data, i, cur_agent) == 0
                    tries = -1; % leave the loop
                end
                tries = tries - 1;
            end
            if tries > -1
                %remove the last agent
                data.floor(i).agents = data.floor(i).agents(1:end-1);
            end
        end
```

```
        data.total_agent_count = data.total_agent_count +
            length(data.floor(i).agents);

        if length(data.floor(i).agents) ~= agent_count
            fprintf(['WARNING: could only place %d agents on floor %d ' ...
                'instead of the desired %d.\n'], ...
                length(data.floor(i).agents), i, agent_count);
        end
    end
end
if floors_with_agents==0
    error('no spots to place agents!');
end

end
```

Listing 7: initAgents.m

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

for i=1:data.floor_count

    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) =  1;

if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;

elseif i>data.floor_exit
        boundary_data(data.floor(i).img_stairs_down) = -1;

    else
        boundary_data(data.floor(i).img_exit) = -1;

end
    exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    [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)
% initialize the internal data from the config data
%
%  arguments:
%   config      data structure from loadConfig()
%
```

```
%  return:
%   data        data structure: all internal data used for the main loop
%
%               all internal data is stored in pixels NOT in meters


data = config;

%for convenience
data.pixel_per_meter = 1/data.meter_per_pixel;

fprintf('Init escape routes...\n');
data = initEscapeRoutes(data);
fprintf('Init wall forces...\n');
data = initWallForces(data);
fprintf('Init agents...\n');
data = initAgents(data);

% maximum influence of agents on each other

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

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

% floors plot
data.figure_floors=figure;
% figure('units','normalized','outerposition',[0 0 1 1])
data.figure_floors_subplots_w = data.floor_count;
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
end

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

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

% prepare video file name
data.video_file_name = ['video_' data.frame_basename '.avi'];

% 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
v = str2double(values);
idx = ~isnan(v);
values(idx) = num2cell(v(idx));

config = cell2struct(values, keynames);


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

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

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

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

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

    config.floor(i).img_exit = (img_build(:, :, 1) ==   0 ...
                              & img_build(:, :, 2) ~=   0 ...
```

```
                                  & img_build(:, :, 3) ==   0);


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

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


    if i == config.floor_exit

        %make the exit_nr matrix where the number of exit is indicated in
            each
        %pixel

        %make a zeroes matrix as big as img_exit
        config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

        %make a zeros vector as long as floor_exit
        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
            config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));

        end
    end

    %init the plot image here, because this won't change
    config.floor(i).img_plot = 5*config.floor(i).img_wall ...
        + 4*config.floor(i).img_stairs_up ...
        + 3*config.floor(i).img_stairs_down ...
        + 2*config.floor(i).img_exit ...
        + 1*config.floor(i).img_spawn;
    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
        0 0];
end
```

Listing 11: 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 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
% to run, you need to load the output first:
% load('output_FILENAME');

% tabula rasa
clc

% read in data from output
agents_per_floor = output.agents_per_floor;
config = output.config;
exit_left = output.exit_left;
simulation_time_real = output.simulation_time;
dt = config.dt;
deleted_agents = output.deleted_agents;


% get users screen size
screen_size = get(0, 'ScreenSize');

% agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:length(agents_per_floor)));

% check if whole simulation was performed
steps=config.duration/dt-1;
for i=1:steps
    if agents_on_boat(i)<0
        steps=i-2;
        break
    end
```

```
end

simulation_time_sim = steps*dt;

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;

% find out t10, t50, t90, t100
t10=0;
for i=1:steps
    if agents_left(i)<agents_start/10
        t10=t10+dt;
    end
end
if t10~=0
    t10=t10+dt;
end

t50=0;
for i=1:steps
    if agents_left(i)<agents_start/2
        t50=t50+dt;
    end
end
if t50~=0
    t50=t50+dt;
end

t90=0;
for i=1:steps
    if agents_left(i)<agents_start*0.9
        t90=t90+dt;
    end
end
if t90~=0
    t90=t90+dt;
end

t99=0;
for i=1:steps
    if agents_left(i)<agents_start*0.99
        t99=t99+dt;
    end
end
if t99~=0
    t99=t99+dt;
end
```

```
t100=0;
if agents_left==agents_start
    for i=1:steps
        if agents_left(i)<agents_start
            t100=t100+dt;
        end
    end
end

% create time axis
if t100~=0
    time = [0:dt:t100];
else
    time = [0:dt:simulation_time_sim];
end
steps = length(time);

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;
agents_per_floor = agents_per_floor(:,1:1:steps);
exit_left = exit_left(:,1:1:steps);

% plot agents left over time
f1 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
plot(time/60,agents_left/agents_start*100,'LineWidth', 2)
axis([0 13 0 100])
title(sprintf('rescued agents (of total %i agents)',agents_start));
xlabel('time [min]')
ylabel('rescued agents out of all agents [%]')

% plot agents_per_floor over time
f2 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.floor_count,1);
color = hsv(config.floor_count);
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)

axis([0 13 0 1000])
```

```
title(sprintf('agents per floor (of total %i agents)',agents_start));
xlabel('time [min]')
ylabel('agents per floor')

% plot free places in rescue boats over time
f3 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.exit_count/2,1);
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
legend(list)

axis([0 13 0 200])
title('rescue boat capacity');
xlabel('time [min]')
ylabel('free places on rescue boat')

% scale plots up to screen size
set(f1, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f2, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f3, 'Position', [0 0 screen_size(3) screen_size(4) ] );


% print out

fprintf('Timestep: %f s\n', dt)
fprintf('Steps simulated: %i\n', steps)
fprintf('Simulation time: %f min\n', simulation_time_sim/60)
fprintf('Agents on ship on start: %i\n', agents_start)
fprintf('Agents on ship on simulation end: %i\n', agents_on_boat(end))
fprintf('Agents deleted due to NaN-positions: %i\n', deleted_agents)

fprintf('t_10: %f\n', t10)
fprintf('t_50: %f\n', t50)
fprintf('t_90: %f\n', t90)
fprintf('t_99: %f\n', t99)
fprintf('t_100: %f\n', t100)
```

Listing 15: plotFloor.m

```
function simulate(config_file)
```

```
% run this to start the simulation

% start recording the matlab output window for debugging reasons
diary log

if nargin==0
    config_file='../data/config1.conf';
end

fprintf('Load config file...\n');
config = loadConfig(config_file);

data = initialize(config);

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

% tic until simulation end
simstart = tic;

%make video while simulation
if data.save_frames==1
           vidObj=VideoWriter(data.video_file_name);
           open(vidObj);
        end

while (data.time < data.duration)
    % tic until timestep end
    tstart=tic;
    data = addDesiredForce(data);
    data = addWallForce(data);
    data = addAgentRepulsiveForce(data);
    data = applyForcesAndMove(data);

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

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

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

        % do the plotting
        set(0,'CurrentFigure',data.figure_floors);
        for floor=1:data.floor_count
            plotAgentsPerFloor(data, floor);
```

```
            plotFloor(data, floor);
        end

        if data.save_frames==1
%               print('-depsc2',sprintf('frames/%s_%04i.eps', ...
%                   data.frame_basename,data.step), data.figure_floors);

%           make video while simulate
            currFrame=getframe(data.figure_floors);
            writeVideo(vidObj,currFrame);

        end

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

        if data.agents_exited == data.total_agent_count
            fprintf('All agents are now saved (or are they?). Time: %.2f
                sec\n', data.time);
            fprintf('Total Agents: %i\n', data.total_agent_count);

            print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
                data.frame_basename), data.figure_floors);
            break;
        end

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

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

    end

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

    % update time
    if (data.time + data.dt > data.duration)
        data.dt = data.duration - data.time;
        data.time = data.duration;
    else
        data.time = data.time + data.dt;
    end
```

```
end

%make video while simulation
close(vidObj);

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

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

% save diary
diary
```

Listing 16: simulate.m

9.1.2 *control exit* code

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

% Obstruction effects in case of physical interaction

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

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

    % update range tree of lower floor
    tree_lower = tree;

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

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

    for ai = 1:agents_on_floor
        pi = data.floor(fi).agents(ai).p;
        vi = data.floor(fi).agents(ai).v;
```

```
        ri = data.floor(fi).agents(ai).r;

        % use range tree to get the indices of all agents near agent ai
        idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
                               pi(2) - r_max, pi(2) + r_max)';

        % 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;

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

                % distance of agents
                d = norm(nij);

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

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

                % repulsive interaction forces
                if d < rij
                   T1 = data.k*(rij - d);
                   T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
                else
                   T1 = 0;
                   T2 = 0;
                end

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

                data.floor(fi).agents(ai).f = ...
                    data.floor(fi).agents(ai).f + F;
                data.floor(fi).agents(aj).f = ...
                    data.floor(fi).agents(aj).f - F;
            end
        end

        % include agents on stairs!
        if fi > 1
            % use range tree to get the indices of all agents near agent ai
```

```
    if ~isempty(data.floor(fi-1).agents)
        idx = rangeQuery(tree_lower, pi(1) - r_max, ...
                pi(1) + r_max, pi(2) - r_max, pi(2) + r_max)';

        % if there are any agents...
        if ~isempty(idx)
            for aj = idx
                pj = data.floor(fi-1).agents(aj).p;
                if data.floor(fi-1).img_stairs_up(round(pj(1)),
                    round(pj(2)))

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

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

                    % distance of agents
                    d = norm(nij);

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

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

                    % repulsive interaction forces
                    if d < rij
                       T1 = data.k*(rij - d);
                       T2 = data.kappa*(rij - d)*dot((vj -
                          vi),tij)*tij;
                    else
                       T1 = 0;
                       T2 = 0;
                    end

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

                    data.floor(fi).agents(ai).f = ...
                        data.floor(fi).agents(ai).f + F;
                    data.floor(fi-1).agents(aj).f = ...
                        data.floor(fi-1).agents(aj).f - F;
                end
            end
        end
    end
end
```

```
    end
end
```

Listing 17: addAgentRepulsiveForce.m

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

for fi = 1:data.floor_count

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

        % get agent's data
        p = data.floor(fi).agents(ai).p;
        m = data.floor(fi).agents(ai).m;
        v0 = data.floor(fi).agents(ai).v0;
        v = data.floor(fi).agents(ai).v;
        numbr= data.floor(fi).agents(ai).nr;

        %control exit

         if data.control_exit==1

            %even agents
                if numbr==0;
            % get direction towards nearest exit
                ex = lerp2(data.floor(fi).img_dir_x_even, p(1), p(2));
                ey = lerp2(data.floor(fi).img_dir_y_even, p(1), p(2));
                e = [ex ey];
                 % get force
                Fi = m * (v0*e - v)/data.tau;

                % add force
                data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f
                    + Fi;
                end

                %odd agents
                if numbr==1;
            % get direction towards nearest exit
                ex = lerp2(data.floor(fi).img_dir_x_odd, p(1), p(2));
                ey = lerp2(data.floor(fi).img_dir_x_odd, p(1), p(2));
                 e = [ex ey];
                % get force
                 Fi = m * (v0*e - v)/data.tau;

                % add force
                 data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f
                     + Fi;
```

```
                end


        else



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

        % get force
        Fi = m * (v0*e - v)/data.tau;

        % add force
        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
         end
    end
end
```

Listing 18: 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;

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

Listing 19: 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];

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

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

        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
               data.floor(fi).agents(ai).clogged =
                   data.floor(fi).agents(ai).clogged + 1;
               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))
               if data.floor(fi).agents(ai).clogged >= 40
                    nx = rand(1)*2 - 1;
                    ny = rand(1)*2 - 1;
                    n = [nx ny];
                    v = n*data.v_max/2;
                    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))

                   % get agent's new position
                   newp = data.floor(fi).agents(ai).p + ...
                   v * data.dt / data.meter_per_pixel;
                   if isnan(newp)
                        % get rid of disturbing agent
                        fprintf('WARNING: position of an agent is NaN!
                            Deleted this agent.\n')
                        exited(ai) = 1;
                        data.agents_exited = data.agents_exited +1;
                        data.output.deleted_agents=data.output.deleted_agents+1;
                        newp = [1 1];
```

```
                    end
                end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this
                agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end


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

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

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

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

%             fprintf('agent exited from upper loop\n');

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

%             fprintf(int2str(data.current_exit));

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

            %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));

                 %redo initEscapeRoutes and initWallForces with new exit
                     and wall parameters

                if data.control_exit~=1
                data = initEscapeRoutes(data);

                %control exits
                else
                    if data.floor(fi).agents(ai).nr==0   %agents with
                       number 0 --> only use  even exits

                 data = initEscapeRoutes_even(data);

                    else
                 data = initEscapeRoutes_odd(data);
                    end
                end
                data = initWallForces(data);

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

            end
        end
    end

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

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




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

    % 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 of 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];

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

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


        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
               data.floor(fi).agents(ai).clogged =
                   data.floor(fi).agents(ai).clogged + 1;
```

```
               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))
               if data.floor(fi).agents(ai).clogged >= 40
                    nx = rand(1)*2 - 1;
                    ny = rand(1)*2 - 1;
                    n = [nx ny];
                    v = n*data.v_max/2;
                    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))

                   % get agent's new position
                   newp = data.floor(fi).agents(ai).p + ...
                   v * data.dt / data.meter_per_pixel;
                   if isnan(newp)
                        % get rid of disturbing agent
                        fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
                        exited(ai) = 1;
                        data.agents_exited = data.agents_exited +1;
                        data.output.deleted_agents=data.output.deleted_agents+1;
                        newp = [1 1];
                   end
               end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end

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

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

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

        % check if agent reached an exit
        if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
```

```
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;

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

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

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

                        %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));

                %redo initEscapeRoutes and initWallForces with new exit
                    and wall parameters
                if data.control_exit~=1
                data = initEscapeRoutes(data);

                %control exits
                else

                    if data.floor(fi).agents.nr==0; %agent with number ==
                        0 , only use even numbers

                 data = initEscapeRoutes_even(data);

                    else

                 data = initEscapeRoutes_odd(data);

                    end
                end
                data = initWallForces(data);

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

            end
```

```
            end
        end

        % add appropriate agents to next lower floor
        if fi < data.floor_exit
            data.floor(fi+1).agents = [data.floor(fi+1).agents ...
                                       data.floor(fi).agents(floorchange)];
        end

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

% if n_velocity_clamps > 0
%     fprintf(['WARNING: clamped velocity of %d agents, ' ...
%               'possible simulation instability.\n'], n_velocity_clamps);
% end
```

Listing 20: 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

val = 0;

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

% check for agent intersection
for i=1:length(data.floor(floor_idx).agents)
    if i~=agent_idx
        if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
            ...
                <= r +  data.floor(floor_idx).agents(i).r
            val=2;
            return;
        end
    end
```

```matlab
end

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

Listing 21: checkForIntersection.m

```matlab
mex 'fastSweeping.c'
mex 'getNormalizedGradient.c'
mex 'lerp2.c'
mex 'createRangeTree.c'
mex 'rangeQuery.c'
```

Listing 22: compileC.m

```matlab
function data = initAgents(data)

% place agents randomly in desired spots, without overlapping



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

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

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

    if ~isempty(x)
        floors_with_agents = floors_with_agents + 1;
        for j=1:agent_count
            cur_agent = length(data.floor(i).agents) + 1;

            % init agent
            data.floor(i).agents(cur_agent).r = getAgentRadius();
            data.floor(i).agents(cur_agent).v = [0, 0];
            data.floor(i).agents(cur_agent).f = [0, 0];
            data.floor(i).agents(cur_agent).m = data.m;
            data.floor(i).agents(cur_agent).v0 = data.v0;
            data.floor(i).agents(cur_agent).clogged = 0; %to check if
                agent is hanging in the wall
```

```
            %control exit

            data.floor(i).agents(cur_agent).nr=logical(round(rand(1)));

            %even-->0
            %odd-->1

            tries = 10;
            while tries > 0
                % randomly pick a spot and check if it's free
                idx = randi(length(x));
                data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
                if checkForIntersection(data, i, cur_agent) == 0
                    tries = -1; % leave the loop
                end
                tries = tries - 1;
            end
            if tries > -1
                %remove the last agent
                data.floor(i).agents = data.floor(i).agents(1:end-1);
            end
        end
        data.total_agent_count = data.total_agent_count +
            length(data.floor(i).agents);

        if length(data.floor(i).agents) ~= agent_count
            fprintf(['WARNING: could only place %d agents on floor %d ' ...
                'instead of the desired %d.\n'], ...
                length(data.floor(i).agents), i, agent_count);
        end
    end
end
if floors_with_agents==0
    error('no spots to place agents!');
end

end
```

Listing 23: initAgents.m

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

for i=1:data.floor_count

    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) =  1;
```

```
if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;

elseif i>data.floor_exit
        boundary_data(data.floor(i).img_stairs_down) = -1;

    else
        boundary_data(data.floor(i).img_exit) = -1;

end
    exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
        getNormalizedGradient(boundary_data, -exit_dist);
end
```

Listing 24: initEscapeRoutes.m

```
function data = initEscapeRoutes_even(data)
%INITESCAPEROUTES Summary of this function goes here
%   Detailed explanation goes here
%only even numbered rescue boats are exits


for i=1:data.floor_count

    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) =  1;

if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;


elseif i>data.floor_exit
        boundary_data(data.floor(i).img_stairs_down) = -1;

else


        temp1=double(mod(data.exit_nr,2));   %matrix in which every number
            which is even turns to zero, odd turns to one
%           temp2=logical((data.floor(i).img_exit)-(temp1));
%           boundary_data(temp2)=-1;              %boundary_data considers
    only the exits with even numbers --> set -1 where those are
        temp2=((data.floor(i).img_exit)-(temp1));
        temp3=logical(mod(temp2,2));
        boundary_data(temp3)=-1;


```

```
end

fprintf('Init escaperoutes_even...\n');
    exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    [data.floor(i).img_dir_x_even, data.floor(i).img_dir_y_even] = ...
        getNormalizedGradient(boundary_data, -exit_dist);



end
```

Listing 25: initEscapeRoutes_even.m

```
function data = initEscapeRoutes_odd(data)
%INITESCAPEROUTES Summary of this function goes here
%   Detailed explanation goes here
%only odd numbered rescue boats are exits


for i=1:data.floor_count

    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) =  1;

if i<data.floor_exit

    boundary_data(data.floor(i).img_stairs_up) = -1;


elseif i>data.floor_exit
        boundary_data(data.floor(i).img_stairs_down) = -1;


    else

        temp=logical(mod(data.exit_nr,2));   %matrix in which every number
           which is even turns to zero, odd turns to one
        boundary_data(temp) = -1;      %boundary_data considers only the
           exits with odd numbers

end


fprintf('Init escaperoutes_odd...\n');
    exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    [data.floor(i).img_dir_x_odd, data.floor(i).img_dir_y_odd] = ...
        getNormalizedGradient(boundary_data, -exit_dist);

```

```

end
```

Listing 26: initEscapeRoutes_odd.m

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


data = config;

%for convenience
data.pixel_per_meter = 1/data.meter_per_pixel;

fprintf('Init escape routes...\n');
if data.control_exit~=1
    data = initEscapeRoutes(data);

    %control exits




else

    data = initEscapeRoutes_even(data);
    data = initEscapeRoutes_odd(data);
end

fprintf('Init wall forces...\n');
data = initWallForces(data);
fprintf('Init agents...\n');
data = initAgents(data);

% maximum influence of agents on each other

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

fprintf('Init plots...\n');
%init the plots
%exit plot
```

```
data.figure_exit=figure;
hold on;
axis([0 data.duration 0 data.total_agent_count]);
title(sprintf('agents that reached the exit (total agents: %i)',
    data.total_agent_count));

% floors plot
data.figure_floors=figure;
% figure('units','normalized','outerposition',[0 0 1 1])
data.figure_floors_subplots_w = data.floor_count;
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
end

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

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

% prepare video file name
data.video_file_name = ['video_' data.frame_basename '.avi'];

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

Listing 27: 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 28: 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
v = str2double(values);
idx = ~isnan(v);
values(idx) = num2cell(v(idx));

config = cell2struct(values, keynames);

```

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

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

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

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


%pixel is exit if 1-->0, 3-->0, and if 2 is between 255 and 230 or if no
%red or blue

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


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

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


    if i == config.floor_exit

        %make the exit_nr matrix where the number of exit is indicated in each
        %pixel

        %make a zeroes matrix as big as img_exit
        config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

        %make a zeros vector as long as floor_exit
        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
            config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));

        end
    end

    %init the plot image here, because this won't change
    config.floor(i).img_plot = 5*config.floor(i).img_wall ...
        + 4*config.floor(i).img_stairs_up ...
        + 3*config.floor(i).img_stairs_down ...
        + 2*config.floor(i).img_exit ...
        + 1*config.floor(i).img_spawn;
    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
        0 0];
end
```

Listing 29: 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 30: plotAgentsPerFloor.m

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

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

Listing 31: 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 32: plotFloor.m

```
% post processing of output.mat data from simulation
% to run, you need to load the output first:
% load('output_FILENAME');

% tabula rasa
clc
```

```
% read in data from output
agents_per_floor = output.agents_per_floor;
config = output.config;
exit_left = output.exit_left;
simulation_time_real = output.simulation_time;
dt = config.dt;
deleted_agents = output.deleted_agents;


% get users screen size
screen_size = get(0, 'ScreenSize');

% agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:length(agents_per_floor)));

% check if whole simulation was performed
steps=config.duration/dt-1;
for i=1:steps
    if agents_on_boat(i)<0
        steps=i-2;
        break
    end
end

simulation_time_sim = steps*dt;

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;

% find out t10, t50, t90, t100
t10=0;
for i=1:steps
    if agents_left(i)<agents_start/10
        t10=t10+dt;
    end
end
if t10~=0
    t10=t10+dt;
end

t50=0;
for i=1:steps
    if agents_left(i)<agents_start/2
        t50=t50+dt;
    end
end
if t50~=0
```

```
    t50=t50+dt;
end

t90=0;
for i=1:steps
    if agents_left(i)<agents_start*0.9
        t90=t90+dt;
    end
end
if t90~=0
    t90=t90+dt;
end

t99=0;
for i=1:steps
    if agents_left(i)<agents_start*0.99
        t99=t99+dt;
    end
end
if t99~=0
    t99=t99+dt;
end

t100=0;
if agents_left==agents_start
    for i=1:steps
        if agents_left(i)<agents_start
            t100=t100+dt;
        end
    end
end

% create time axis
if t100~=0
    time = [0:dt:t100];
else
    time = [0:dt:simulation_time_sim];
end
steps = length(time);

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;
agents_per_floor = agents_per_floor(:,1:1:steps);
exit_left = exit_left(:,1:1:steps);

% plot agents left over time
f1 = figure;
hold on
```

```
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
plot(time/60,agents_left/agents_start*100,'LineWidth', 2)
axis([0 13 0 100])
title(sprintf('rescued agents (of total %i agents)',agents_start));
xlabel('time [min]')
ylabel('rescued agents out of all agents [%]')

% plot agents_per_floor over time
f2 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.floor_count,1);
color = hsv(config.floor_count);
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)

axis([0 13 0 1000])
title(sprintf('agents per floor (of total %i agents)',agents_start));
xlabel('time [min]')
ylabel('agents per floor')

% plot free places in rescue boats over time
f3 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.exit_count/2,1);
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
legend(list)

axis([0 13 0 200])
title('rescue boat capacity');
xlabel('time [min]')
ylabel('free places on rescue boat')

% scale plots up to screen size
```

```
set(f1, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f2, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f3, 'Position', [0 0 screen_size(3) screen_size(4) ] );


% print out

fprintf('Timestep: %f s\n', dt)
fprintf('Steps simulated: %i\n', steps)
fprintf('Simulation time: %f min\n', simulation_time_sim/60)
fprintf('Agents on ship on start: %i\n', agents_start)
fprintf('Agents on ship on simulation end: %i\n', agents_on_boat(end))
fprintf('Agents deleted due to NaN-positions: %i\n', deleted_agents)

fprintf('t_10: %f\n', t10)
fprintf('t_50: %f\n', t50)
fprintf('t_90: %f\n', t90)
fprintf('t_99: %f\n', t99)
fprintf('t_100: %f\n', t100)
```

Listing 33: plotFloor.m

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

% start recording the matlab output window for debugging reasons
diary log

if nargin==0
    config_file='../data/config1.conf';
end

fprintf('Load config file...\n');
config = loadConfig(config_file);

data = initialize(config);

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

% tic until simulation end
simstart = tic;

%make video while simulation
if data.save_frames==1
            vidObj=VideoWriter(data.video_file_name);
            open(vidObj);
        end
```

```
while (data.time < data.duration)
    % tic until timestep end
    tstart=tic;
    data = addDesiredForce(data);
    data = addWallForce(data);
    data = addAgentRepulsiveForce(data);
    data = applyForcesAndMove(data);

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

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

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

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

        if data.save_frames==1
%             print('-depsc2',sprintf('frames/%s_%04i.eps', ...
%                 data.frame_basename,data.step), data.figure_floors);

%           make video while simulate
            currFrame=getframe(data.figure_floors);
            writeVideo(vidObj,currFrame);

        end

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

        if data.agents_exited == data.total_agent_count
            fprintf('All agents are now saved (or are they?). Time: %.2f
                sec\n', data.time);
            fprintf('Total Agents: %i\n', data.total_agent_count);

            print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
                data.frame_basename), data.figure_floors);
            break;
        end

        % toc of timestep
```

```
        data.telapsed = toc(tstart);
        % toc of whole simulation
        data.output.simulation_time = toc(simstart);

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

    end

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

    % update time
    if (data.time + data.dt > data.duration)
        data.dt = data.duration - data.time;
        data.time = data.duration;
    else
        data.time = data.time + data.dt;
    end

end

%make video while simulation
close(vidObj);

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

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

% save diary
diary
```

Listing 34: simulate.m

9.1.3 *C* code

```

#include <mex.h>
#include <string.h>
```

```c
#include "tree_build.c"
#include "tree_query.c"
#include "tree_free.c"

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

    if (nlhs < 1)
        return;

    points = (point_t*) mxGetPr(prhs[0]);
    m = mxGetM(prhs[0]);
    n = mxGetN(prhs[0]);

    if (m != 2)
        mexErrMsgTxt("...");

    tree = build_tree(points, n);

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

    root_index = (int*) data;
    *root_index = tree->root_index;
    memcpy(data + sizeof(int), tree->data, tree->first_free);

    free_tree(tree);
}
```

Listing 35: createRangeTree.c

```c
#include "mex.h"

#include <math.h>

#if defined __GNUC__ && defined __FAST_MATH__ && !defined __STRICT_ANSI__
#define MIN(i, j) fmin(i, j)
#define MAX(i, j) fmax(i, j)
#define ABS(i)    fabs(i)
#else
#define MIN(i, j) ((i) < (j) ? (i) : (j))
#define MAX(i, j) ((i) > (j) ? (i) : (j))
#define ABS(i)    ((i) < 0.0 ? -(i) : (i))
```

```
#endif


#define SOLVE_AND_UPDATE    udiff = uxmin - uymin; \
                            if (ABS(udiff) >= 1.0) \
                            { \
                                up = MIN(uxmin, uymin) + 1.0; \
                            } \
                            else \
                            { \
                                up = (uxmin + uymin + sqrt(2.0 - udiff *
                                    udiff)) / 2.0; \
                                up = MIN(uij, up); \
                            } \
                            err_loc = MAX(ABS(uij - up), err_loc); \
                            u[ij] = up;

#define I_STEP(_uxmin, _uymin, _st) if (boundary[ij] == 0.0) \
                                    { \
                                        uij = un; \
                                        un = u[ij + _st]; \
                                        uxmin = _uxmin; \
                                        uymin = _uymin; \
                                        SOLVE_AND_UPDATE \
                                        ij += _st; \
                                    } \
                                    else \
                                    { \
                                        up = un; \
                                        un = u[ij + _st]; \
                                        ij += _st; \
                                    }




#define I_STEP_UP(_uxmin, _uymin)   I_STEP(_uxmin, _uymin, 1)
#define I_STEP_DOWN(_uxmin, _uymin) I_STEP(_uxmin, _uymin,-1)

#define UX_NEXT un
#define UX_PREV up
#define UX_BOTH MIN(UX_PREV, UX_NEXT)

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

```

```c
static void iteration(double *u, double *boundary, int m, int n, double
    *err)
{
    int i, j, ij;
    int m2, n2;
    double up, un, uij, uxmin, uymin, udiff, err_loc;

    m2 = m - 2;
    n2 = n - 2;

    *err = 0.0;
    err_loc = 0.0;

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

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

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

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

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

        I_STEP_UP(UX_PREV, UY_BOTH)
    }

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

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

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


    /* sweep 2 */
    /* i = 0, j = n-1 */
```

```
    ij = (n-1)*m;
    un = u[ij];
    I_STEP_UP(UX_NEXT, UY_LEFT)

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

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

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

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

        I_STEP_UP(UX_PREV, UY_BOTH)
    }

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

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

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

    /* sweep 3 */
    /* i = m-1, j = n-1 */
    ij = m*n - 1;
    un = u[ij];
    I_STEP_DOWN(UX_NEXT, UY_LEFT)

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

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

    /* i = m-1->0, j = n2->1 */
```

```
    for (j = n2; j >= 1; --j)
    {
        I_STEP_DOWN(UX_NEXT, UY_BOTH)

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

        I_STEP_DOWN(UX_PREV, UY_BOTH)
    }

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

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

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

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

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

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

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

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

        I_STEP_DOWN(UX_PREV, UY_BOTH)
    }

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

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

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

    *err = MAX(*err, err_loc);
}

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

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

    /* Get inputs */
    if (nrhs < 1)
        mexErrMsgTxt("At least 1 input argument needed.");
    else if (nrhs > 3)
        mexErrMsgTxt("At most 3 input arguments used.");



    /* Get boundary */
    if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
        mexErrMsgTxt("Boundary field needs to be a full double precision
            matrix.");

    boundary = mxGetPr(prhs[0]);
    m = mxGetM(prhs[0]);
    n = mxGetN(prhs[0]);
    entries = m * n;

    /* Get max iterations  */
    if (nrhs >= 2)
    {
        if (!mxIsDouble(prhs[1]) || mxGetM(prhs[1]) != 1 ||
            mxGetN(prhs[1]) != 1)
             mexErrMsgTxt("Maximum iteration needs to be positive
                 integer.");
        max_iter = (int) *mxGetPr(prhs[1]);
```

```
        if (max_iter <= 0)
            mexErrMsgTxt("Maximum iteration needs to be positive
                integer.");
    }
    else
        max_iter = 20;

    /* Get tolerance */
    if (nrhs >= 3)
    {
        if (!mxIsDouble(prhs[2]) || mxGetM(prhs[2]) != 1 ||
            mxGetN(prhs[2]) != 1)
            mexErrMsgTxt("Tolerance needs to be a positive real number.");
        tol = *mxGetPr(prhs[2]);
        if (tol < 0)
            mexErrMsgTxt("Tolerance needs to be a positive real number.");
    }
    else
        tol = 1e-12;


    /* create and init output (distance) matrix */
    plhs[0] = mxCreateDoubleMatrix(m, n, mxREAL);
    u = mxGetPr(plhs[0]);

    for (i = 0; i < entries; ++i)
        u[i] = boundary[i] < 0.0 ? 0.0 : 1.0e10;

    err = 0.0;
    i = 0;
    do
    {
        iteration(u, boundary, m, n, &err);
        ++i;
    } while (err > tol && i < max_iter);
}
```

Listing 36: fastSweeping.c

```
#include "mex.h"

#include <math.h>

#define INTERIOR(i, j)  (boundary[(i) + m*(j)] == 0)

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

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

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

    /* Get inputs */
    if (nrhs < 2)
        mexErrMsgTxt("At least 2 input argument needed.");
    else if (nrhs > 2)
        mexErrMsgTxt("At most 2 input argument used.");



    /* Get boundary */
    if (!mxIsDouble(prhs[0]) || mxIsClass(prhs[0], "sparse"))
        mexErrMsgTxt("Boundary field needs to be a full double precision matrix.");

    boundary = mxGetPr(prhs[0]);
    m = mxGetM(prhs[0]);
    n = mxGetN(prhs[0]);

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

    dist = mxGetPr(prhs[1]);
    m = mxGetM(prhs[1]);
    n = mxGetN(prhs[1]);

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



    for (j = 0; j < n; ++j)
        for (i = 0; i < m; ++i)
```

```
            if (INTERIOR(i,j))
            {
                if (i > 0)
                    dxm = INTERIOR(i-1,j) ? DIST(i-1,j) : DIST(i,j);
                else
                    dxm = DIST(i,j);

                if (i < m-1)
                    dxp = INTERIOR(i+1,j) ? DIST(i+1,j) : DIST(i,j);
                else
                    dxp = DIST(i,j);

                if (j > 0)
                    dym = INTERIOR(i,j-1) ? DIST(i,j-1) : DIST(i,j);
                else
                    dym = DIST(i,j);

                if (j < n-1)
                    dyp = INTERIOR(i,j+1) ? DIST(i,j+1) : DIST(i,j);
                else
                    dyp = DIST(i,j);

                XGRAD(i, j) = (dxp - dxm) / 2.0;
                YGRAD(i, j) = (dyp - dym) / 2.0;
                nrm = sqrt(XGRAD(i, j)*XGRAD(i, j) + YGRAD(i, j)*YGRAD(i,
                    j));
                if (nrm > 1e-12)
                {
                    XGRAD(i, j) /= nrm;
                    YGRAD(i, j) /= nrm;
                }
            }
            else
            {
                XGRAD(i, j) = 0.0;
                YGRAD(i, j) = 0.0;
            }

    for (j = 0; j < n; ++j)
        for (i = 0; i < m; ++i)
            if (!INTERIOR(i, j))
            {
                xns = 0.0;
                yns = 0.0;
                nn = 0;
                if (i > 0 && INTERIOR(i-1,j))
                {
                    xns += XGRAD(i-1,j);
                    yns += YGRAD(i-1,j);
                    ++nn;
```

```
                }
                if (i < m-1 && INTERIOR(i+1,j))
                {
                    xns += XGRAD(i+1,j);
                    yns += YGRAD(i+1,j);
                    ++nn;
                }
                if (j > 0 && INTERIOR(i,j-1))
                {
                    xns += XGRAD(i,j-1);
                    yns += YGRAD(i,j-1);
                    ++nn;
                }
                if (j < n-1 && INTERIOR(i,j+1))
                {
                    xns += XGRAD(i,j+1);
                    yns += YGRAD(i,j+1);
                    ++nn;
                }

                if (nn > 0)
                {
                    XGRAD(i, j) = xns / nn;
                    YGRAD(i, j) = yns / nn;
                }
            }
}
```

Listing 37: getNormalizedGradient.c

```

#include <mex.h>

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

    if (nlhs < 1)
        return;
    else if (nlhs > 1)
        mexErrMsgTxt("Exactly one output argument needed.");

    if (nrhs != 3)
        mexErrMsgTxt("Exactly three input arguments needed.");

    m = mxGetM(prhs[0]);
    n = mxGetN(prhs[0]);
```

```
    data = mxGetPr(prhs[0]);
    x = *mxGetPr(prhs[1]) - 1;
    y = *mxGetPr(prhs[2]) - 1;

    plhs[0] = mxCreateDoubleMatrix(1, 1, mxREAL);
    out = mxGetPr(plhs[0]);

    x = x < 0 ? 0 : x > m - 1 ? m - 1 : x;
    y = y < 0 ? 0 : y > n - 1 ? n - 1 : y;
    i0 = (int) x;
    j0 = (int) y;
    i1 = i0 + 1;
    i1 = i1 > m - 1 ? m - 1 : i1;
    j1 = j0 + 1;
    j1 = j1 > n - 1 ? n - 1 : j1;

    idx00 = i0 + m * j0;
    d00 = data[idx00];
    d01 = data[idx00 + m];
    d10 = data[idx00 + 1];
    d11 = data[idx00 + m + 1];

    wx1 = x - i0;
    wy1 = y - j0;
    wx0 = 1.0 - wx1;
    wy0 = 1.0 - wy1;

    *out = wx0 * (wy0 * d00 + wy1 * d01) + wx1 * (wy0 * d10 + wy1 * d11);
}
```

Listing 38: lerp2.c

```
#include <mex.h>
#include <string.h>

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

void mexFunction(int nlhs, mxArray *plhs[], int nrhs, const mxArray
   *prhs[])
{
    tree_t *tree;
    int n, i;
    int *point_idx, *root_idx;
    range_t *range;
    uchar *data;

    if (nlhs != 1)
```

```
        mexErrMsgTxt("...");

    if (nrhs < 5)
        mexErrMsgTxt("...");
    else if (nrhs > 5)
        mexErrMsgTxt("...");

    data = (uchar*) mxGetPr(prhs[0]);

    tree = (tree_t*) malloc(sizeof(tree_t));
    tree->first_free = mxGetM(prhs[0]) - sizeof(int);
    tree->total_size = tree->first_free;
    root_idx = (int*) data;
    tree->root_index = *root_idx;
    tree->data = data + sizeof(int);

    n = mxGetN(prhs[0]);
    if (n != 1)
        mexErrMsgTxt("...");

    range = range_query(tree, *mxGetPr(prhs[1]), *mxGetPr(prhs[2]),
       *mxGetPr(prhs[3]), *mxGetPr(prhs[4]));

    plhs[0] = mxCreateNumericMatrix(range->n, 1, mxUINT32_CLASS, mxREAL);
    point_idx = (int*) mxGetPr(plhs[0]);

    for (i = 0; i < range->n; ++i)
        point_idx[i] = range->point_idx[i] + 1;

    free_range(range);
    free(tree);
}
```

Listing 39: rangeQuery.c

```
#ifndef TREE_H
#define TREE_H

#include "tree_types.h"

/* build a 2D range tree using the given points */
tree_t* build_tree(point_t *points, int n);

/* query a range tree */
range_t* range_query(tree_t *tree, double x_min, double x_max, double
    y_min, double y_max);

/* free memory of a tree */
void free_tree(tree_t *tree);
```

```
/* free memory of a range */
void free_range(range_t *range);

#endif
```

Listing 40: tree.h

```
#ifndef TREE_BUILD_H
#define TREE_BUILD_H

#include "tree.h"

/* recursively build a subtree */
int build_subtree(tree_t *tree, double *x_vals, const int nx, point_t
    *points, int *point_idx, const int np);

/* double comparison for qsort */
int compare_double(const void *a, const void *b);

/* index array sorting functions, sort point index array by point y
    coordinates */
void index_sort_y(const point_t *points, int *point_idx, const int n);
void index_quicksort_y(const point_t *points, int *point_idx, int l, int
    r);
int index_partition_y(const point_t *points, int *point_idx, int l, int r);

#endif
```

Listing 41: tree_build.h

```

#include <assert.h>
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

#include "tree_build.h"

tree_t* build_tree(point_t *points, int n)
{
    int nx, i, j, *point_idx;
    double *x_vals;
    tree_t *tree;

    /* get x coordinate values of all points */
    x_vals = (double*) malloc(n * sizeof(double));
    for (i = 0; i < n; ++i)
        x_vals[i] = points[i].x;

    /* sort x values */
```

```
    qsort(x_vals, n, sizeof(double), compare_double);

    /* count number of unique x values */
    nx = 1;
    for (i = 1; i < n; ++i)
        if (x_vals[i] != x_vals[i - 1])
            ++nx;

    /* remove duplicates */
    j = 0;
    for (i = 0; i < nx; ++i)
    {
        x_vals[i] = x_vals[j];
        while (x_vals[i] == x_vals[j])
            ++j;
    }

    /* create an index array */
    point_idx = (int*) malloc(n * sizeof(int));
    for (i = 0; i < n; ++i)
        point_idx[i] = i;

    /* sort index array by y coordinates of associated points */
    index_sort_y(points, point_idx, n);

    /* init tree */
    tree = (tree_t*) malloc(sizeof(tree_t));
    tree->total_size = n * sizeof(point_t);
    tree->data = (uchar*) malloc(tree->total_size);

    /* copy point coordinates to tree data */
    memcpy(tree->data, points, n * sizeof(point_t));

    /* set first free byte and root index of the tree */
    tree->first_free = n * sizeof(point_t);
    tree->root_index = tree->first_free;

    /* recursively build tree */
    build_subtree(tree, x_vals, nx, points, point_idx, n);

    /* free temporaries */
    free(x_vals);
    return tree;
}


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;

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

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

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

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

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

        /* count points belonging to the left child */
        np_left = 0;
        for (i = 0; i < np; ++i)
        {
            if (points[point_idx[i]].x <= node->x_val)
                ++np_left;
        }
```

```
        /* allocate memory for children's index arrays */
        point_idx_left = (int*) malloc(np_left * sizeof(int));
        point_idx_right = (int*) malloc((np - np_left) * sizeof(int));

        /* fill index arrays */
        j = 0;
        k = 0;
        for (i = 0; i < np; ++i)
        {
            if (points[point_idx[i]].x <= node->x_val)
                point_idx_left[j++] = point_idx[i];
            else
                point_idx_right[k++] = point_idx[i];
        }

        /* free current node's temporary index array */
        free(point_idx);

        /* build left subtree */
        build_subtree(tree, x_vals, nx_left, points, point_idx_left,
            np_left);

        /* build right subtree and get its root node index */
        right_idx = build_subtree(tree, x_vals + nx_left, nx - nx_left,
            points, point_idx_right, np - np_left);
        /* update node pointer (could have changed during build_subtree,
            because of data allocation) */
        node = (node_t*) &tree->data[node_idx];
        /* update node's right child index */
        node->right_idx = right_idx;
    }

    /* return node index to parent */
    return node_idx;
}

int compare_double(const void *a, const void *b)
{
    double ad, bd;
    ad = *((double*) a);
    bd = *((double*) b);
    return (ad < bd) ? -1 : (ad > bd) ? 1 : 0;
}

void index_sort_y(const point_t *points, int *point_idx, const int n)
{
    index_quicksort_y(points, point_idx, 0, n - 1);
}

void index_quicksort_y(const point_t *points, int *point_idx, int l, int r)
```

```c
{
    int p;

    /* quicksort point indices by point y coordinates, don't touch point
        array itself */
    while (l < r)
    {
        p = index_partition_y(points, point_idx, l, r);
        if (r - p > p - l)
        {
            index_quicksort_y(points, point_idx, l, p - 1);
            l = p + 1;
        }
        else
        {
            index_quicksort_y(points, point_idx, p + 1, r);
            r = p - 1;
        }
    }
}

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

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

    /* quicksort partition */
    do
    {
        while (points[point_idx[i]].y <= pivot && i < r)
            ++i;

        while (points[point_idx[j]].y >= pivot && j > l)
            --j;

        if (i < j)
        {
            tmp = point_idx[i];
            point_idx[i] = point_idx[j];
            point_idx[j] = tmp;
        }
    } while (i < j);

    if (points[point_idx[i]].y > pivot)
    {
```

```c
        tmp = point_idx[i];
        point_idx[i] = point_idx[r];
        point_idx[r] = tmp;
    }

    return i;
}
```

Listing 42: tree_build.c

```c

#include <stdlib.h>

#include "tree.h"

void free_tree(tree_t *tree)
{
    free(tree->data);
}

void free_range(range_t *range)
{
    free(range->point_idx);
}
```

Listing 43: tree_free.c

```c
#ifndef TREE_QUERY_H
#define TREE_QUERY_H

#include "tree_types.h"

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

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

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

#endif
```

Listing 44: tree_query.h

```c

#include <assert.h>
#include <stdio.h>
#include <stdlib.h>

```

```c
#include "tree_query.h"

#define LEFT_CHILD_IDX(node_idx, node)  (node_idx) + sizeof(node_t) +
    (node)->np * sizeof(int)
#define RIGHT_CHILD_IDX(node_idx, node) (node)->right_idx
#define NODE_FROM_IDX(tree, node_idx)   (node_t*) &(tree)->data[node_idx];

range_t* range_query(tree_t *tree, double x_min, double x_max, double
    y_min, double y_max)
{
    int split_node_idx, node_idx;
    node_t *split_node, *node;
    range_t *range;

    /* init range */
    range = (range_t*) malloc(sizeof(range_t));
    range->min.x = x_min;
    range->max.x = x_max;
    range->min.y = y_min;
    range->max.y = y_max;
    range->n = 0;
    range->total_size = 16;
    range->point_idx = (int*) malloc(range->total_size * sizeof(int));

    /* find split node */
    split_node_idx = find_split_node(tree, tree->root_index, range);
    split_node = NODE_FROM_IDX(tree, split_node_idx);

    /* if split node is a child */
    if (split_node->right_idx == -1)
    {
        range_query_y(tree, split_node_idx, range);
        return range;
    }

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

```c
    /* 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)
{
    node_t *node;

    node = (node_t*) &tree->data[node_idx];
    /* check if this node is the split node */
    if (range->min.x <= node->x_val && range->max.x > node->x_val)
        return node_idx;
```

```c

    /* ...or if it is a child (and therefor the split node) */
    if (node->right_idx == -1)
        return node_idx;

    /* otherwise search the split node at the left or right of the current
       node */
    if (range->max.x <= node->x_val)
        return find_split_node(tree, LEFT_CHILD_IDX(node_idx, node),
            range);
    else
        return find_split_node(tree, RIGHT_CHILD_IDX(node_idx, node),
            range);
}

void range_query_y(tree_t *tree, int node_idx, range_t *range)
{
    point_t *points;
    double y;
    int i, j, k, m, start, end;
    int *point_idx;
    node_t *node;

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

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

    /* binary search for lower end of the range */
    y = range->min.y;
    j = 0;
    k = node->np - 1;
    while (j != k)
    {
        m = (j + k) / 2;
        if (points[point_idx[m]].y >= y)
            k = m;
        else
            j = m + 1;
    }
    start = j;

    /* binary search for higher end of the range */
    y = range->max.y;
    j = 0;
    k = node->np - 1;
```

```c
    while (j != k)
    {
        m = (j + k + 1) / 2;
        if (points[point_idx[m]].y > y)
            k = m - 1;
        else
            j = m;
    }
    end = j;

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

}
```

Listing 45: tree_query.c

```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*/
    int root_index;
} tree_t;

/* node */
typedef struct
{
```

```
    /* index of the right child node (left child follows directly after
        current) */
    int right_idx;

    /* number of associated points */
    int np;

    /* associated x-coordinate value */
    double x_val;
} node_t;

/* range */
typedef struct
{
    /* point index list */
    int *point_idx;

    /* number of saved indices */
    int n;

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

    /* minimum range point */
    point_t min;

    /* maximum range point */
    point_t max;
} range_t;

#endif
```

Listing 46: tree_types.h

9.1.4 *crew command* code

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

% Obstruction effects in case of physical interaction

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

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

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

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

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

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

        % use range tree to get the indices of all agents near agent ai
        idx = rangeQuery(tree, pi(1) - r_max, pi(1) + r_max, ...
                                    pi(2) - r_max, pi(2) + r_max)';

        % 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;

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

                % distance of agents
                d = norm(nij);

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

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

                % repulsive interaction forces
                if d < rij
                   T1 = data.k*(rij - d);
                   T2 = data.kappa*(rij - d)*dot((vj - vi),tij)*tij;
                else
                   T1 = 0;
                   T2 = 0;
```

```
                end

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

                data.floor(fi).agents(ai).f = ...
                    data.floor(fi).agents(ai).f + F;
                data.floor(fi).agents(aj).f = ...
                    data.floor(fi).agents(aj).f - F;
            end
        end

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

                % if there are any agents...
                if ~isempty(idx)
                    for aj = idx
                        pj = data.floor(fi-1).agents(aj).p;
                        if data.floor(fi-1).img_stairs_up(round(pj(1)),
                            round(pj(2)))

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

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

                            % distance of agents
                            d = norm(nij);

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

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

                            % repulsive interaction forces
                            if d < rij
                               T1 = data.k*(rij - d);
                               T2 = data.kappa*(rij - d)*dot((vj -
                                   vi),tij)*tij;
                            else
                               T1 = 0;
                               T2 = 0;
```

```
                            end

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

                            data.floor(fi).agents(ai).f = ...
                                data.floor(fi).agents(ai).f + F;
                            data.floor(fi-1).agents(aj).f = ...
                                data.floor(fi-1).agents(aj).f - F;
                        end
                    end
                end
            end
        end
    end
end
```

Listing 47: addAgentRepulsiveForce.m

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

for fi = 1:data.floor_count

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

        % get agent's data
        p = data.floor(fi).agents(ai).p;
        m = data.floor(fi).agents(ai).m;
        v0 = data.floor(fi).agents(ai).v0;
        v = data.floor(fi).agents(ai).v;


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

        % get force
        Fi = m * (v0*e - v)/data.tau;

        % add force
        data.floor(fi).agents(ai).f = data.floor(fi).agents(ai).f + Fi;
    end
end
```

Listing 48: 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;

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

Listing 49: 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];

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

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

        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
               data.floor(fi).agents(ai).clogged =
                   data.floor(fi).agents(ai).clogged + 1;
```

```
               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))
               if data.floor(fi).agents(ai).clogged >= 40
                    nx = rand(1)*2 - 1;
                    ny = rand(1)*2 - 1;
                    n = [nx ny];
                    v = n*data.v_max/2;
                    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))

                   % get agent's new position
                   newp = data.floor(fi).agents(ai).p + ...
                   v * data.dt / data.meter_per_pixel;
                   if isnan(newp)
                        % get rid of disturbing agent
                        fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
                        exited(ai) = 1;
                        data.agents_exited = data.agents_exited +1;
                        data.output.deleted_agents=data.output.deleted_agents+1;
                        newp = [1 1];
                   end
               end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end


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

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

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

        % check if agent reached an exit
```

```
        if data.floor(fi).img_exit(round(newp(1)), round(newp(2)))
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;

%             fprintf('agent exited from upper loop\n');

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

%             fprintf(int2str(data.current_exit));

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

            %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));

                %redo initEscapeRoutes and initWallForces with new exit
                    and wall parameters
                data = initEscapeRoutes(data);
                data = initWallForces(data);

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

            end
        end
    end

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

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

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

    % 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 of 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];

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

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

```

```
        % check if agents position is ok
        % repositioning after 50 times clogging
        % deleting if agent has a NaN position
        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];
               data.floor(fi).agents(ai).clogged =
                   data.floor(fi).agents(ai).clogged + 1;
               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))
               if data.floor(fi).agents(ai).clogged >= 40
                    nx = rand(1)*2 - 1;
                    ny = rand(1)*2 - 1;
                    n = [nx ny];
                    v = n*data.v_max/2;
                    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))

                   % get agent's new position
                   newp = data.floor(fi).agents(ai).p + ...
                   v * data.dt / data.meter_per_pixel;
                   if isnan(newp)
                        % get rid of disturbing agent
                        fprintf('WARNING: position of an agent is NaN!
                            Deleted this agent.\n')
                        exited(ai) = 1;
                        data.agents_exited = data.agents_exited +1;
                        data.output.deleted_agents=data.output.deleted_agents+1;
                        newp = [1 1];
                   end
               end
            end
        else
            % get rid of disturbing agent
            fprintf('WARNING: position of an agent is NaN! Deleted this
                agent.\n')
            exited(ai) = 1;
            data.agents_exited = data.agents_exited +1;
            data.output.deleted_agents=data.output.deleted_agents+1;
            newp = [1 1];
        end

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

        % reset forces for next timestep
```

```
        data.floor(fi).agents(ai).f = [0 0];

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

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

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

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

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

                        %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));

                %redo initEscapeRoutes and initWallForces with new exit
                    and wall parameters
                data = initEscapeRoutes(data);
                data = initWallForces(data);

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

            end

        end
    end

    % add appropriate agents to next lower floor
    if fi < data.floor_exit
        data.floor(fi+1).agents = [data.floor(fi+1).agents ...
                                   data.floor(fi).agents(floorchange)];
```

```
    end

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

if data.switch_done==0 && data.step ~=1 &&
   data.open_on_x_agents_on_boat>sum(data.output.agents_per_floor(:,data.step-1))
     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;
     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)
end

% if n_velocity_clamps > 0
%     fprintf(['WARNING: clamped velocity of %d agents, ' ...
%             'possible simulation instability.\n'], n_velocity_clamps);
% end
```

Listing 50: 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

val = 0;

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

% check for agent intersection
for i=1:length(data.floor(floor_idx).agents)
    if i~=agent_idx
```

```
        if norm(data.floor(floor_idx).agents(i).p-p)*data.meter_per_pixel
            ...
                <= r +  data.floor(floor_idx).agents(i).r
            val=2;
            return;
        end
    end
end


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

Listing 51: checkForIntersection.m

```
mex 'fastSweeping.c'
mex 'getNormalizedGradient.c'
mex 'lerp2.c'
mex 'createRangeTree.c'
mex 'rangeQuery.c'
```

Listing 52: compileC.m

```
function data = initAgents(data)

% place agents randomly in desired spots, without overlapping



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

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

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

    if ~isempty(x)
        floors_with_agents = floors_with_agents + 1;
        for j=1:agent_count
            cur_agent = length(data.floor(i).agents) + 1;

```

```
            % init agent
            data.floor(i).agents(cur_agent).r = getAgentRadius();
            data.floor(i).agents(cur_agent).v = [0, 0];
            data.floor(i).agents(cur_agent).f = [0, 0];
            data.floor(i).agents(cur_agent).m = data.m;
            data.floor(i).agents(cur_agent).v0 = data.v0;
            data.floor(i).agents(cur_agent).clogged = 0; %to check if
                agent is hanging in the wall

            tries = 10;
            while tries > 0
                % randomly pick a spot and check if it's free
                idx = randi(length(x));
                data.floor(i).agents(cur_agent).p = [y(idx), x(idx)];
                if checkForIntersection(data, i, cur_agent) == 0
                    tries = -1; % leave the loop
                end
                tries = tries - 1;
            end
            if tries > -1
                %remove the last agent
                data.floor(i).agents = data.floor(i).agents(1:end-1);
            end
        end
        data.total_agent_count = data.total_agent_count +
            length(data.floor(i).agents);

        if length(data.floor(i).agents) ~= agent_count
            fprintf(['WARNING: could only place %d agents on floor %d ' ...
                'instead of the desired %d.\n'], ...
                length(data.floor(i).agents), i, agent_count);
        end
    end
end
if floors_with_agents==0
    error('no spots to place agents!');
end

end
```

Listing 53: initAgents.m

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

for i=1:data.floor_count

    boundary_data = zeros(size(data.floor(i).img_wall));
    boundary_data(data.floor(i).img_wall) =  1;
```

```
if i<data.floor_exit
    boundary_data(data.floor(i).img_stairs_up) = -1;

elseif i>data.floor_exit
        boundary_data(data.floor(i).img_stairs_down) = -1;

    else
        boundary_data(data.floor(i).img_exit) = -1;

end
    exit_dist = fastSweeping(boundary_data) * data.meter_per_pixel;
    [data.floor(i).img_dir_x, data.floor(i).img_dir_y] = ...
        getNormalizedGradient(boundary_data, -exit_dist);
end
```

Listing 54: initEscapeRoutes.m

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


data = config;

%for convenience
data.pixel_per_meter = 1/data.meter_per_pixel;

fprintf('Init escape routes...\n');
data = initEscapeRoutes(data);
fprintf('Init wall forces...\n');
data = initWallForces(data);
fprintf('Init agents...\n');
data = initAgents(data);

% maximum influence of agents on each other

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

fprintf('Init plots...\n');
%init the plots
%exit plot
```

```
data.figure_exit=figure;
hold on;
axis([0 data.duration 0 data.total_agent_count]);
title(sprintf('agents that reached the exit (total agents: %i)',
    data.total_agent_count));

% floors plot
data.figure_floors=figure;
% figure('units','normalized','outerposition',[0 0 1 1])
data.figure_floors_subplots_w = data.floor_count;
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
end

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

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

% prepare video file name
data.video_file_name = ['video_' data.frame_basename '.avi'];

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

Listing 55: 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 56: 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
v = str2double(values);
idx = ~isnan(v);
values(idx) = num2cell(v(idx));

config = cell2struct(values, keynames);

```

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

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

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

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

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

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


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

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


    if i == config.floor_exit

        %make the exit_nr matrix where the number of exit is indicated in each
        %pixel

        %make a zeroes matrix as big as img_exit
        config.exit_nr=zeros(size(config.floor(config.floor_exit).img_exit));

        %make a zeros vector as long as floor_exit
        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
            config.exit_left(1,e) = config.(sprintf('exit_%d_nr', e));

        end
    end

    %init the plot image here, because this won't change
    config.floor(i).img_plot = 5*config.floor(i).img_wall ...
        + 4*config.floor(i).img_stairs_up ...
        + 3*config.floor(i).img_stairs_down ...
        + 2*config.floor(i).img_exit ...
        + 1*config.floor(i).img_spawn;
    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 0 0];
end



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

% save the "all exits open" configuration
config.floor(config.floor_exit).img_exit_second = config.floor(config.floor_exit).img_exit;
config.floor(config.floor_exit).img_wall_second = config.floor(config.floor_exit).img_wall;

% replace the open_second exits in img_exit with a wall
for i=1:config.open_second_nr
    config.floor(config.floor_exit).img_wall(find(config.exit_nr == config.open_second(i))) = 1;
    config.floor(config.floor_exit).img_exit(find(config.exit_nr == config.open_second(i))) = 0;
end

% set the boolean to check if switch from first to second mode has already
% been executed
config.switch_done = 0;
```

Listing 57: 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 58: plotAgentsPerFloor.m

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

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

Listing 59: 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 60: plotFloor.m

```
% post processing of output.mat data from simulation
% to run, you need to load the output first:
% load('output_FILENAME');

% tabula rasa
clc

% read in data from output
agents_per_floor = output.agents_per_floor;
config = output.config;
exit_left = output.exit_left;
simulation_time_real = output.simulation_time;
dt = config.dt;
deleted_agents = output.deleted_agents;


% get users screen size
screen_size = get(0, 'ScreenSize');

% agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:length(agents_per_floor)));

% check if whole simulation was performed
steps=config.duration/dt-1;
for i=1:steps
    if agents_on_boat(i)<0
        steps=i-2;
        break
    end
end
```

```
simulation_time_sim = steps*dt;

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;

% find out t10, t50, t90, t100
t10=0;
for i=1:steps
    if agents_left(i)<agents_start/10
        t10=t10+dt;
    end
end
if t10~=0
    t10=t10+dt;
end

t50=0;
for i=1:steps
    if agents_left(i)<agents_start/2
        t50=t50+dt;
    end
end
if t50~=0
    t50=t50+dt;
end

t90=0;
for i=1:steps
    if agents_left(i)<agents_start*0.9
        t90=t90+dt;
    end
end
if t90~=0
    t90=t90+dt;
end

t99=0;
for i=1:steps
    if agents_left(i)<agents_start*0.99
        t99=t99+dt;
    end
end
if t99~=0
    t99=t99+dt;
end

t100=0;
if agents_left==agents_start
```

```
    for i=1:steps
        if agents_left(i)<agents_start
            t100=t100+dt;
        end
    end
end

% create time axis
if t100~=0
    time = [0:dt:t100];
else
    time = [0:dt:simulation_time_sim];
end
steps = length(time);

% recalculate agents on boat
agents_on_boat = sum(agents_per_floor(:,1:1:steps));
agents_start = agents_on_boat(1);
agents_left = agents_start-agents_on_boat;
agents_per_floor = agents_per_floor(:,1:1:steps);
exit_left = exit_left(:,1:1:steps);

% plot agents left over time
f1 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
plot(time/60,agents_left/agents_start*100,'LineWidth', 2)
axis([0 13 0 100])
title(sprintf('rescued agents (of total %i agents)',agents_start));
xlabel('time [min]')
ylabel('rescued agents out of all agents [%]')

% plot agents_per_floor over time
f2 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.floor_count,1);
color = hsv(config.floor_count);
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)

axis([0 13 0 1000])
title(sprintf('agents per floor (of total %i agents)',agents_start));
xlabel('time [min]')
```

```
ylabel('agents per floor')

% plot free places in rescue boats over time
f3 = figure;
hold on
grid on
set(gca,'XTick',[1:1:13],'FontSize',16)
list = cell(config.exit_count/2,1);
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
legend(list)

axis([0 13 0 200])
title('rescue boat capacity');
xlabel('time [min]')
ylabel('free places on rescue boat')

% scale plots up to screen size
set(f1, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f2, 'Position', [0 0 screen_size(3) screen_size(4) ] );
set(f3, 'Position', [0 0 screen_size(3) screen_size(4) ] );


% print out

fprintf('Timestep: %f s\n', dt)
fprintf('Steps simulated: %i\n', steps)
fprintf('Simulation time: %f min\n', simulation_time_sim/60)
fprintf('Agents on ship on start: %i\n', agents_start)
fprintf('Agents on ship on simulation end: %i\n', agents_on_boat(end))
fprintf('Agents deleted due to NaN-positions: %i\n', deleted_agents)

fprintf('t_10: %f\n', t10)
fprintf('t_50: %f\n', t50)
fprintf('t_90: %f\n', t90)
fprintf('t_99: %f\n', t99)
fprintf('t_100: %f\n', t100)
```

Listing 61: plotFloor.m

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

```

```
% start recording the matlab output window for debugging reasons
diary log

if nargin==0
    config_file='../data/config1.conf';
end

fprintf('Load config file...\n');
config = loadConfig(config_file);

data = initialize(config);

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

% tic until simulation end
simstart = tic;

%make video while simulation
if data.save_frames==1
           vidObj=VideoWriter(data.video_file_name);
           open(vidObj);
        end

while (data.time < data.duration)
    % tic until timestep end
    tstart=tic;
    data = addDesiredForce(data);
    data = addWallForce(data);
    data = addAgentRepulsiveForce(data);
    data = applyForcesAndMove(data);

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

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

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

        % do the plotting
        set(0,'CurrentFigure',data.figure_floors);
        for floor=1:data.floor_count
            plotAgentsPerFloor(data, floor);
            plotFloor(data, floor);
        end
```

```

        if data.save_frames==1
%             print('-depsc2',sprintf('frames/%s_%04i.eps', ...
%                 data.frame_basename,data.step), data.figure_floors);

%          make video while simulate
            currFrame=getframe(data.figure_floors);
            writeVideo(vidObj,currFrame);

        end

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

        if data.agents_exited == data.total_agent_count
            fprintf('All agents are now saved (or are they?). Time: %.2f sec\n', data.time);
            fprintf('Total Agents: %i\n', data.total_agent_count);

            print('-depsc2',sprintf('frames/exited_agents_%s.eps', ...
                data.frame_basename), data.figure_floors);
            break;
        end

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

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

    end

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

    % update time
    if (data.time + data.dt > data.duration)
        data.dt = data.duration - data.time;
        data.time = data.duration;
    else
        data.time = data.time + data.dt;
    end

end
```

```
%make video while simulation
close(vidObj);

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

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

% save diary
diary
```

Listing 62: simulate.m