ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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

Project Report

Trail Formation

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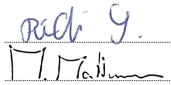
ZÜRICH 11.12.2014	

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Contents

1 Abstract

Agent-based models can provide an easily implementable way to study complex systems. As Helbing et al. (1997) have shown, many aspects of pedestrian motion, such as the formation of trail systems in green areas, can be reproduced using a relatively simple active walker model that takes into account the attractiveness of terrain and feedback on the terrain as it is walked upon. In the current project, we plan to apply this model, and implement the topology of the ground, so that the decisions of peoples can be simulated more accurately. We plan to simulate some simple and idealized situation, to confirm our model and in the end apply it to a real park without trails (like university campus) and see if the result will be the same as in reality. We plan also to apply our model to a bigger park (e.g. Central Park) with all the existing trails/streets and see what would change if peoples can choose in which direction the want to go, without being obligated by tarred streets.

In a first step we are going to implement the model like described in the literature and implement our additions, we will than determine if this model is suitable also to not flat grounds by testing it on some scenarios. In a second step, we will determine the efficiency of already existing trail networks, and see how they would change in time, if they are free to.

We expect to find that in small university campus, natural crated trails will correspond quite well with our model, while parks in cities, with tarred streets will differ in some manner from our results. We suggest that this is caused by the fact that park are not only use to go from a place to an other but also to simply take a walk and therefore not the most direct way is chosen by pedestrian.

2 Individual contributions

The whole project was completed as a team. Since we decided to do this work only in two, both contributed to the implementation of the model in Matlab, the analysis of the achieved results and in writing the final report.

3 Introduction and Motivations

3.1 Introduction

We want to implement a model that can simulate the behaviour of peoples while walking on an open space. We are going to use the already existing model created from Helbing and add the topology of the ground. We have decided to do so because we think it's an important factor involved in the decision of the direction in which to walk and as it, it should be taken into account while simulating the decision of peoples.

First we will simulate some simple situation and try to explain the results of them. In the second part we will instead take some real examples and look how people would walked in a park if they decide to use it only as a passage and therefore not to walk any more on the tarred ways.

3.2 Motivations

We wanted to deal with this subject because it can be found in all day life since it influences the look of every park that can be found in a city.

We decided so also because it seemed to be really interesting as it involves many factors, which can vary from person to person, and therefore the individual trajectory can't be predicted precisely, but the whole set of trails can be predicted well.

3.3 Fundamental Questions

After the implementation of our model we are interested in answering the following questions:

- How do trajectories form?
- What is the final network of the most common sets of entrance / exits?
- How does topology influence the final network?
- How would the system of trails of a real park change over time if the existing "trails" will be no longer asphalted?

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

3.4 Expected Results

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

- The planning of real parks will always be influenced from many parameters, like design, financing mechanism, personal interests, etc. Because of this reasons we expect to find some differences between our model and what we can find in cities.
- In smaller green spaces, like in some university campus, we expect to find great similarities with what predicted from our model. That because there are no existing tarred streets, and pedestrians are therefore free to chose in which direction they want to walk. However in this case we'll find problems in finding information about what are the entrances, exits and haw many peoples are going to pass trough. And because of this also on that case there will be some differences.
- There are many parameters we do not model in our simulation. For example the interaction between pedestrians ("social force"), distractions while walking, etc. By leaving out this details we get a very simplified model. However, we think that these parameters will only minimally affect the motion of pedestrians. We hope therefore to get the same a realistic model capable to predict in accurate way the formation of trail systems.

4 Description of the Model

The ground idea of the model is not complicated and it includes only a few parameter, but its implementation is more complex, because there are many things that must be considered (boundary condition, ...) and it must be made not in a continuous manner, but discrete. In this section only how the model is and not how it is implemented is going to be explained.

The position of a general point on the floor is indicated by the vector $\vec{r}$. The ground structure $G(\vec{r}, t)$ with

$$\vec{r} = \begin{pmatrix} x \\ y \end{pmatrix}$$

is a function which has to contain the information about the presence of trails and its intensity depending on position r and time t. We have decided that the intensity of a trail is in the interval $[0, 1]$: 0 indicate that there is no trail (natural condition) and 1 that the ground has reached the maximum possible intensity of trail. The trail (it's intensity) on a particular place is the result of the sum of the contributions of all pedestrian that have walked on this place and the regeneration of the ground itself. Each pedestrian leave a footprint whit the intensity

$$I \cdot (1 - G(\vec{r}, t))$$

with I a parameter which indicates the intensity of the footprint. So we can say that the equation which describe the evolution of the ground structure is:

$$\frac{dG(\vec{r}, t)}{dt} = -R \cdot G(\vec{r}, t) + I \cdot (1 - G(\vec{r}, t)) \sum_p \delta(\vec{r} - \vec{r_p}(t))$$

with R the parameter for the regeneration ratio, $\delta()$ the Diracs delta function and $\vec{r_p}(t)$ the position of a pedestrian P.

Another function $T(\vec{r})$ defined by the user has to describe the topology of the ground, i.e., for each point $\vec{r}$ the function associates an altitude. Now that we know the topology for each position we have to explain how the pedestrian choose their trajectories. To do this we have to introduce another function $V_p(\vec{r_p}, \vec{r}, t)$, called the ground potential with respect to the person P, which describes the attractiveness of a certain place $\vec{r}$ with respect to the position $\vec{r_p}$ of the person depending on time. The attractiveness of a place depends on two factor:

- The presence of tracks in the neighbourhood
- The slope of the ground between $\vec{r_p}$ and $\vec{r}$

We can say that $V_p(\vec{r_p}, \vec{r}, t) = Z + U_p$, where Z is the part of the potential about the presence of tracks in the neighbourhood of a general place $\vec{r}$ (this part doesn't depend on the position of the person) and U_p is the part of the slope (this instead depends on $\vec{r_p}$). We consider the presence of trails with the factor

$$G(\vec{r'}, t) \cdot \mathrm{e}^{\frac{-\|\vec{r}-\vec{r'}\|}{\sigma}}$$

(where σ is a parameter for the visibility), so that the further a general point $\vec{r}$ with tracks $G(\vec{r}, t)$ is, the less it count. So we can write

$$Z(\vec{r}, t) = \iint_{Ground} G(\vec{r'}, t) \cdot \mathrm{e}^{\frac{-\|\vec{r}-\vec{r'}\|}{\sigma}} \, d\vec{r'}.$$

The slope of the ground is considered with

$$U_p(\vec{r_p}, \vec{r}, t) = -\mathrm{e}^{\frac{-\alpha \cdot \|\vec{r}-\vec{r_p}\|}{|T(\vec{r})-T(\vec{r_p})|}},$$

with $\alpha > 0$ the parameter for slope.

The direction $\vec{d_p}(t)$ of a pedestrian is also given by the weighted (with a scalar parameter l) average of the normalized direction, which indicates the place where the pedestrian want to arrive, and the normalized gradient of the ground potential. In that way if we put the position of the arrival of the pedestrian as $\vec{u_p}$ the direction is

$$\vec{d_p}(\vec{r_p}, t) = \frac{\vec{u_p} - \vec{r_p}(t)}{\|\vec{u_p} - \vec{r_p}(t)\|} + l \cdot \frac{\nabla V(\vec{r_p}(t), t)}{\|\nabla V(\vec{r_p}(t), t)\|}$$

Finally we normalize this direction obtaining

$$\vec{e_p}(\vec{r_p}, t) = \frac{\vec{d_p}(t)}{\|\vec{d_p}(t)\|}$$

in this way we can write the equation of motion of a pedestrian as

$$\frac{d\vec{r_p}(t)}{dt} = v_p \cdot \vec{e_p}(\vec{r_p}, t)$$

with v_p the speed with which the pedestrian is walking.

5 Implementation

5.1 General

As I already said although the model is continuous its implementation on Matlab is done in a discrete manner, so all the function depending on the position are in the code matrix with the dimension dm$\times$ dn. We decided that a cell of the matrix represent 1 m^2 of the ground, so dm and dn are lenght and the large in m of the rectangular field that is considered. Initially we decided that a cell of the matrix was 50cm$\times$50cm to have a high resolution, but the simulations took very long time to be computed, therefore we had to take a compromise. The most important matrix in the code are:

- G2: The ground structure (G in the description of the model). Each cell has the value of the intensity of its own track.
- G4: the potential of the ground depending only on the presence of tracks in the neighbourhood (Z in the description). Each cell has the value of its own potential.
- pot_per: the total potential (V_p in the description)
- G1: the topology (T in the description). Each cell has the value of its own altitude.

5.2 Scripts

The model is composed essentially by 6 scripts:

- 'start.m' in which we can set the parameters and the number of entrances/exits and their position for various simulations. This is also the script that has to been executed in order to make a simulation, because it recall the main script.
- 'main.m' in which the actual simulation take place. Here the variables that were not already been initialised in 'start.m' are defined and the main loop is implemented. The main loop contain the 4 remains scripts and the code for plotting (and capturing) the matrix G2 in order to take a video of the evolution of the ground structure.
- 'change_ground.m' that changes the intensity of the presence of tracks in cells. This is done when a person is on a cell and due to the regeneration ratio of the nature.

- 'insert_person_N_entrance_N_exit.m' that randomly (but with a certain probability) insert a person in one of the N entrances and decide which is his arrival (one of the N exits is chosen).
- 'direction_pend.m' that compute which is the best direction for each person. This is the most complex script in the implementation, therefore in the next subsection a more detailed explanation is given.
- 'move_person.m' that simply if the pedestrian is not already arrived to his target moves him, else he is deleted.

5.3 Explanation of 'direction_pend.m'

The code in this script is dived in two parts: the first compute Z and the second compute V_p and $\vec{e_p}$. In figure 1 the code of the first part. As i already said the

```
1  for aa=1 : dm   % for that goes trough the matrix
2      for bb=1:dn
3          pottot=0; % Sum of all potentials with respect to point [aa bb]
4          for q=1:dm
5              for w=1:dn
6                  if (M(q,w,2)~=0)
7                      pot = M(q,w,2)*exp(-((aa-q)^2 + ...
                           (bb-w)^2)^(1/2)/sigma);% Potential of the ground ...
                           in [q w] respect to [aa bb]
8                      pottot=pottot+ pot; % Sum
9                  end
10             end
11         end
12         pottot = pottot/(dm*dn); % Avarage
13         M(aa,bb,4)=pottot; % Putting the potential in the matrix crated ...
               for it
14     end
15 end
```

Figure 1: First part of code of 'direction_pend.m'

implementation is discrete,therefore the surface integral is here a sum over all the columns and all the rows: the for at line 5 e 6 go through the matrix, line 6 check if the ground potential at point (q,w) is not 0 (this isn't necessary but it increase the performance, because if it is 0 it's useless to compute line 7), line 7 compute the factor $G(\vec{r'}, t) \cdot \mathrm{e}^{\frac{-\|\vec{r}-\vec{r'}\|}{\sigma}}$ and line 8 does the sum. Line 12 divide the sum by the total area of the matrix so that the sum didn't depend on the matrix and line 13 simply

put the result in the matrix of the first part of the potential (in the description Z). This must be done for each cell, because the potential is defined overall, so the loops at line 1 and 2 go through the whole matrix.

The second part of the script is with respect to the position of each person P, so the for at line 1 goes through all the people. The code of this part is in figure 2.

The code from line 6 to line 18 compute the factor $U_p(\vec{r_p}, \vec{r}, t) = -\mathrm{e}^{\frac{-\alpha \cdot \|\vec{r} - \vec{r_p}\|}{|T(\vec{r}) - T(\vec{r_p})|}}$ and does the sum $V_p(\vec{r_p}, \vec{r}, t) = Z + U_p$ (at line 10 or 12 depending on the sign of the slope). Here V_p is the matrix pot_per. This must be done for the hole matrix so the two for at line 4 and 5 go through the matrix. After U_p is computed its gradient and norm are calculated (at line 21 and 22). Then for the people that are not arrived at destination (the distance from destination is calculated at line 23) the normalized vector of the direction is computed in the last part of the code. the code from line 34 to 36 delete the people already arrived at destination.

```
for n=1:num_per  % for all peoples
    if (P(n,5)==0)  % peoples that are not "cancelled"
        pot_per = M(:,:,4);
        for q=1:dm
            for w=1:dn
                dist = ((P(n,1)-q)^2 + (P(n,2)-w)^2)^(1/2); %distance
                if (dist ~=0)
                    pend = (1000*M(q,w,1) - M(P(n,1),P(n,2),1))/dist; %slope
                    if (pend < 0)
                        pot_per(q,w) = M(q,w,4) - exp(1/pend);
                    elseif (pend > 0)
                        pot_per(q,w) = M(q,w,4) - exp(-1/pend);
                    else
                        pot_per(q,w) = M(q,w,4);
                    end
                else
                    pot_per(q,w) = M(q,w,4);
                end
            end
        end
        [fy,fx]=gradient(pot_per(:,:));  % gradient of the potential matrix
        gradnorm = ((fx(P(n,1),P(n,2)))^2 + (fy(P(n,1),P(n,2)))^2)^(1/2);
        distmeta=((P(n,3) - P(n,1))^2 + (P(n,4) - P(n,2))^2)^(1/2);
        if (distmeta ~= 0)
            if (gradnorm ~= 0)
                ex = (P(n,3) - P(n,1))/distmeta + ...
                    fx(P(n,1),P(n,2))*1/gradnorm;
                ey = (P(n,4) - P(n,2))/distmeta + ...
                    fy(P(n,1),P(n,2))*1/gradnorm;
            else
                ex = (P(n,3) - P(n,1))/distmeta;
                ey = (P(n,4) - P(n,2))/distmeta;
            end
            norm = (ex^2 + ey^2)^(1/2);
        else
            M(P(n,1),P(n,2),3) = 0;
            clearvars P(n);
            P(n,5)=1;
        end
        ealfa(n,:) = [ex/norm,ey/norm]; % direction vector
    end
end
```

Figure 2: Second part of code of 'direction_pend.m'

6 Simulation Results and Discussion

6.1 Idealized cases of trail formation

6.1.1 Creation of simple geometries

The first simulation we decided to make, were these with already existing results, so that we could compare our results whit the "correct" ones.

We began whit different types of "squares" with four entrances and four exits. We chose the possibility of entering at an entrance to be the same for each of the four, and the same fore the exits. In that way we covered all possibles ways with the same probability.

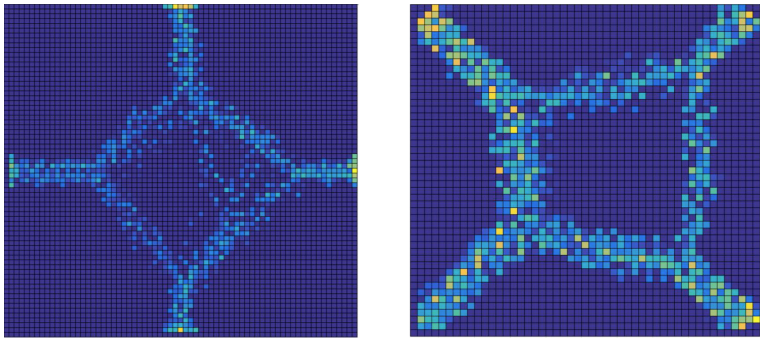

Figure 3: Two simulations with the same set of four entrance/exit but one rotated 45 degrees on a 70x70 m field

The achieved results (see above) matched whit the expected ones already after only 2000 iteration.

This trajectory are the result of the compromise of two fact:

- the lenght of the road traveled from each pedestrian from his entry to the exit has to be minimized,
- for a pedestrian it's better to walk on an already existing trail.

For the second performed simulation we chose a "triangle", three entrances, three exits, and all of them with the same probability.

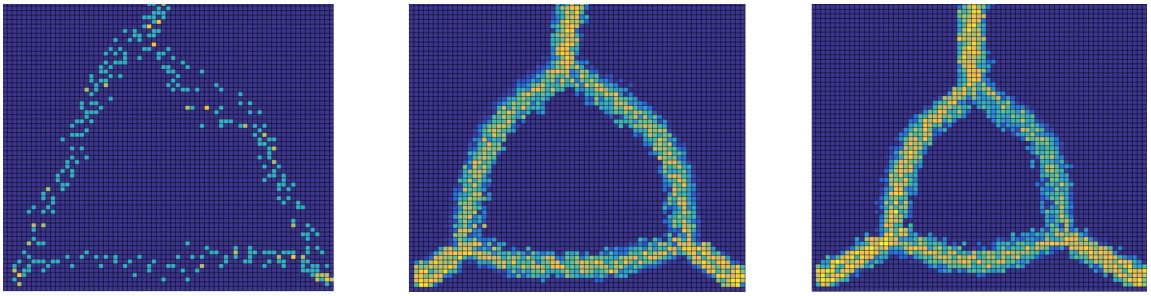

Figure 4: Simulations whit a triangle

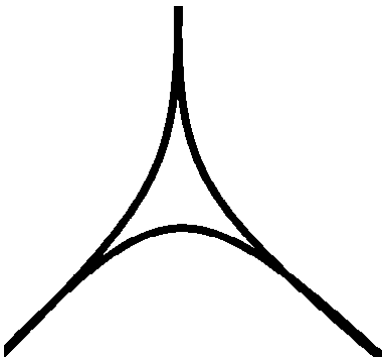

Figure 5: Expected Result of the simulation of the "triangle"

The results were quite different from what we expected. After the first simulation we confirmed that the model was implemented in the correct way, so we expected to find a similar result also in this case, where the trails are going to encounter in the center of the matrix (see figure [5]).

Instead of what we expected, after the first 2000 iterations, we saw the result represented in the middle of figure [4]. The first thought was, there is an error, but all other simulations worked good, so we made another simulation, and after 8000 iterations we became the result shown in last image. In that we can see that the "circle" in the middle is slowly becoming smaller.

We think that the result has this "strange" form, because our model do not consider the inertia of the pedestrian (i.e. that nobody in a normal walk turns suddenly), therefore when the pedestrian reaches the point when his currently trajectory is no more convenient he simply turns in an other one.

6.1.2 Trail formation with already existing trails

One simulation performed with an already existing trail on it is represented in the image below. We took a straight trail and putted the exit on another side of the matrix.

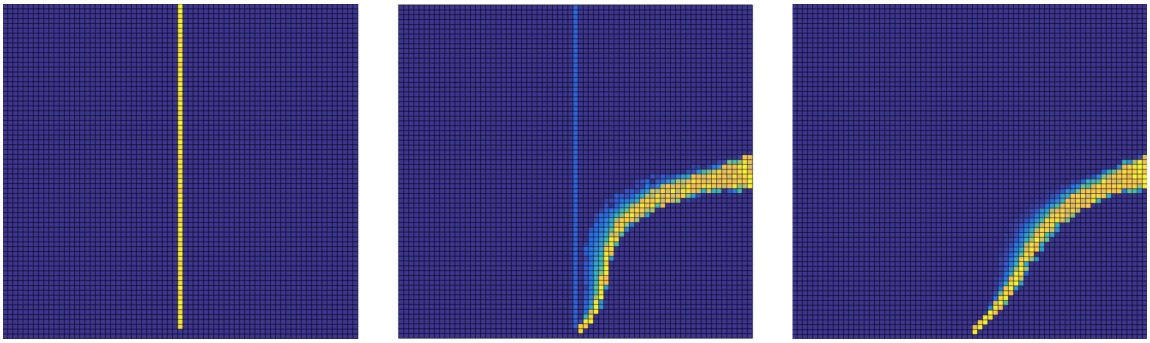

Figure 6: Simulations whit existing trail

The result is exactly what we expected. At the beginning the people follow the existing trail, because it seems easier, but after some iterations, when on the trail which is not used the regeneration of nature begins to become visible, they chose a more direct way. And so at the and we can find an almost straight trail that link directly the entrance with the exit. We suppose that waiting a couple more iterations the trail will become perfectly straight.

6.1.3 Trail formation on a not flat ground

As we see in figure [7] the model with the implementation of the topology work quite well. In this simulation was set that the pedestrian entered in the right respectively left entrance could only go to the right respectively left exit and the topology is shown in the fourth picture. In the first image we can see the simulation after only a few iteration, note that the pedestrian tend to walk on the level lines. The second image show the result after 2000 iterations: the to ways are more close together due to the fact that they are attracted to each other. In the third image (after 5000 iteration) a compromise between the level lines and the attractiveness is reached and the trails are stable.

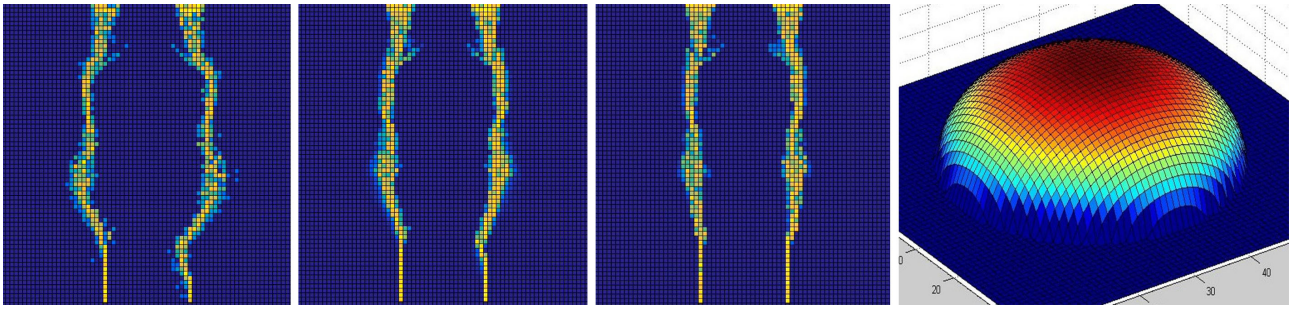

Figure 7: Simulation with topology

6.2 Simulations on a real Park

To answer our last question we simulated the behavior of our model on some real parks. In this part of our work we encountered some problems: after having started the first simulation with a small part of Central Park we saw that our model was too slow for such a big Matrix, it took hardly an hour to make only one iteration. The search for a new Park wasn't so easy: all parks found in cities were too big or not appropriate for our purpose (for example there were buildings in the middle or some others obstacle like a river)

6.2.1 Green Park in London

After a few days of performance improvement of the implementation of the model the simulation speed had doubled so we decided to take some pieces of Green Park (situated in London).

Figure [8] illustrates the entire Park with existing Trail-Systems. The red rectangles shows wich pieces of this Park we took for our simulations.

The obtained results were quite interesting. The first simulation (see figure [9]) went quite how expected, peoples began to walk along the existing streets, but chose in the end a different trail system wich is definitely shorter than the initial one.

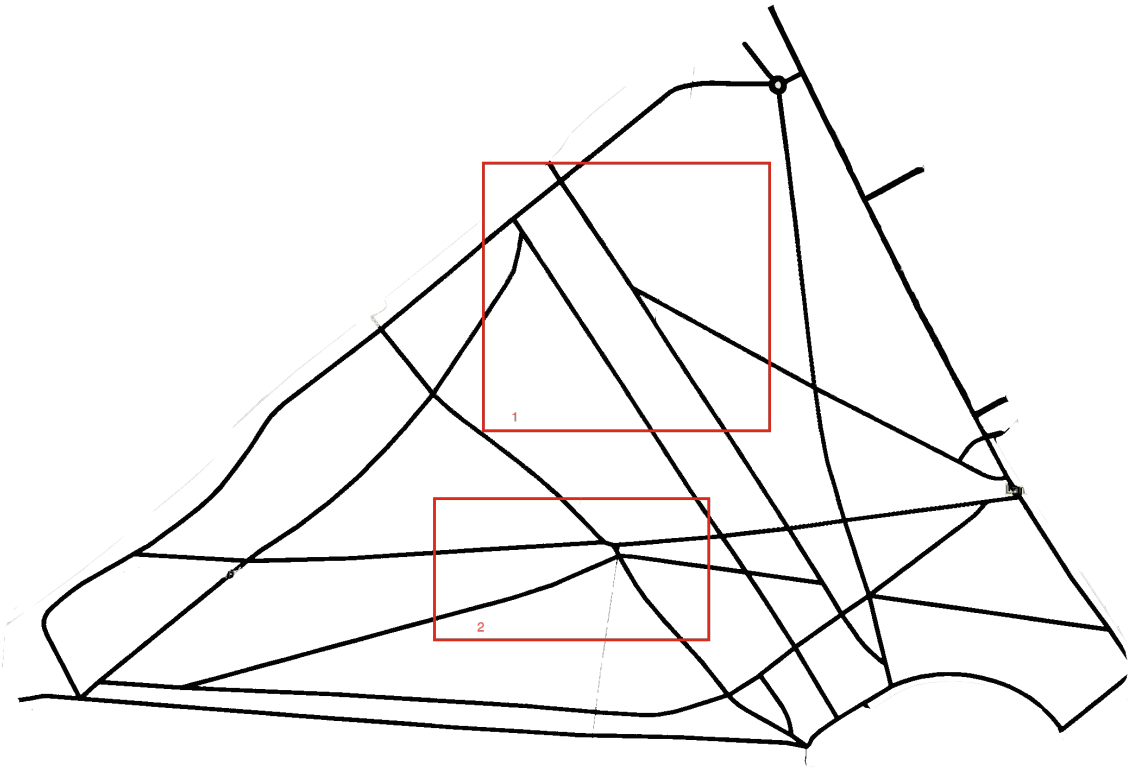

Figure 8: GreenPark

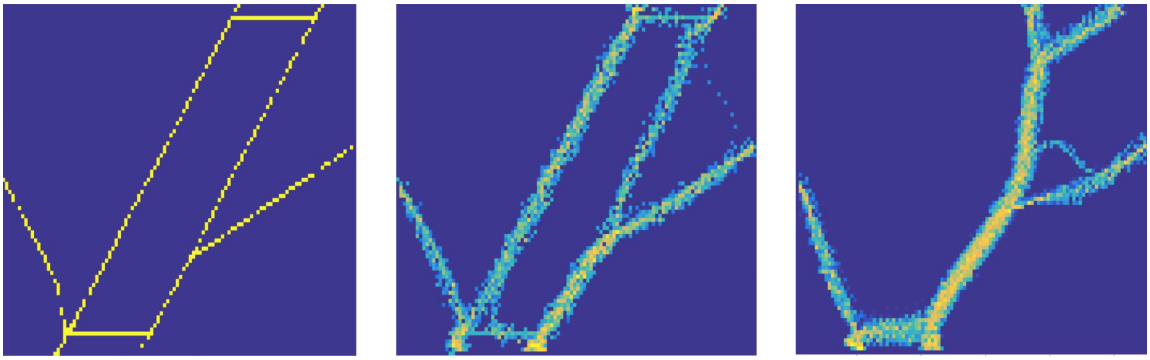

Figure 9: Simulation 1

The second one (see figure [10]) was instead quite surprising. Already at the beginning of the simulations peoples wer not following the streets, instead they began

to form new trails that were quite different from the initial ones.

We could explain these results only in two different ways:

- The part of Park, used in the first simulation, was better planned and therefore also the one chosen from the peoples in our simulation.
- We had only luck, because in the end the obtained results are in both cases similar to each other.

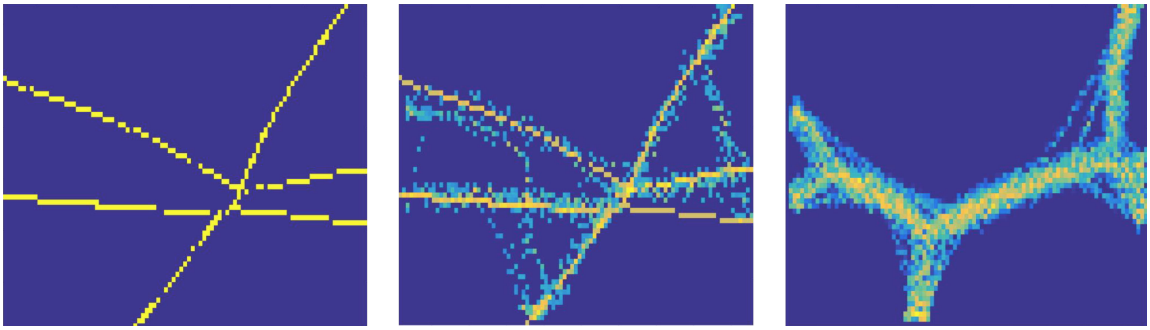

Figure 10: Simulation 2

6.2.2 Joyce Kilmer Park in Manhattan

We found than also some simpler and smaller Parks to use for our simulations. One of these is the Joyce Kilmer Park (see the trail network in fig.[11]).

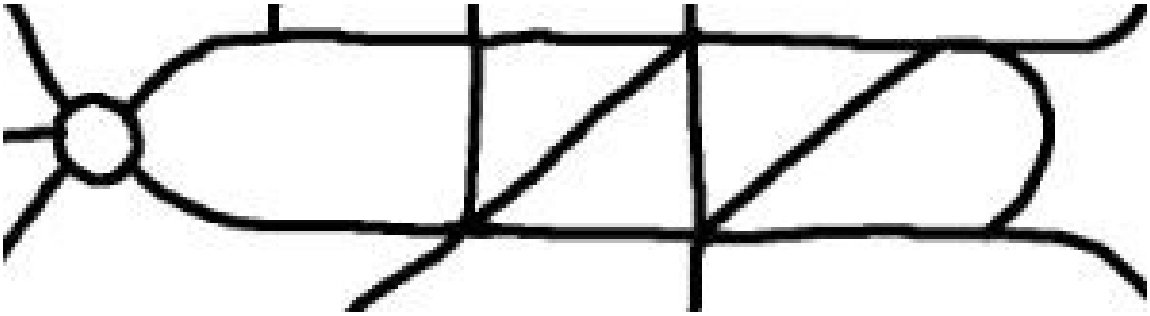

Figure 11: Joyce Park

Also for this park we were not able to find datas about the percentage of peoples entering at each entrance, respectively using the different exits. We therefore chose a logical option, on the left part, where there are three entrances/exists in a small

area we chose to use a smaller probability to appear or go to. The same for the three entrances on the top of the image (for exact datas see in the .m file).

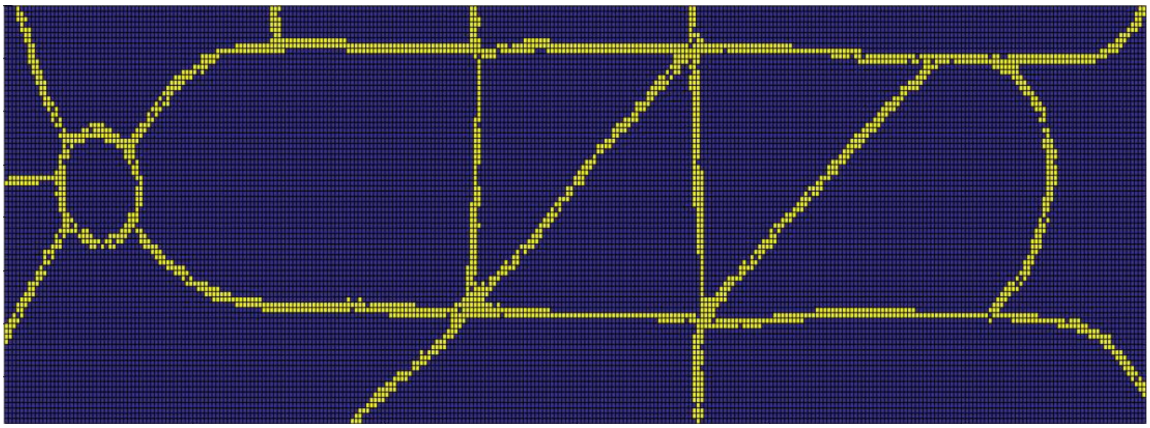

Figure 12: Simulation on Joyce Park at the beginning

We chose to make a simulation with 10′000 iterations. At the beginning peoples chose to walk along the existing network. This went on up to approximately 1′000 iterations, after that they begin to chose their own ways across the Park. In fig. [13] we can see how the first ones began to chose the new ways.

We notated that the first change appeared in the region of the round on the left side of the Park. This modification seems quite logical, but in reality impossible because of a fountain in the center of that round. Unfortunately we were not able to implement a model that includes the possibility of declaring a "black zone" were peoples should not be able to go.

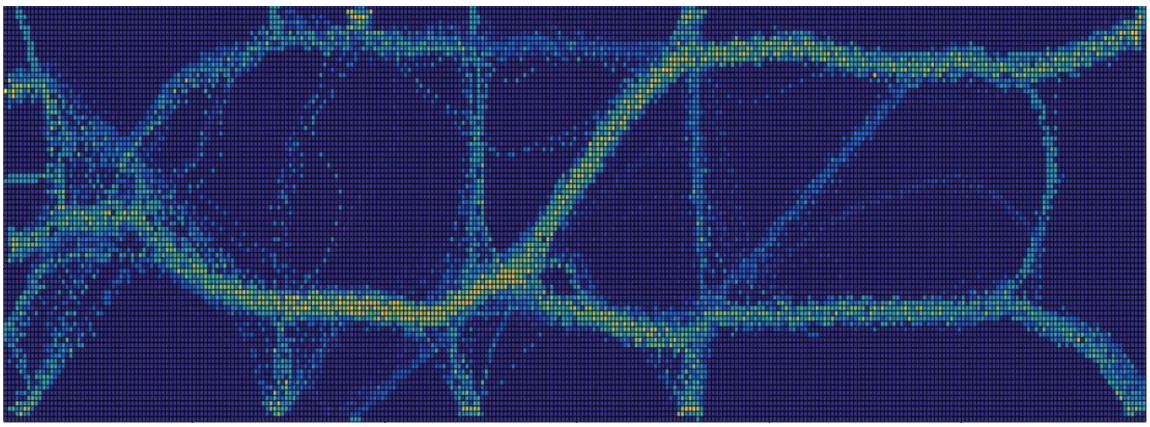

Figure 13: Simulation on Joyce Park after 2000 iterations

After another 3′000 iterations on the right part of the Trail network changed only the diagonal street, while on the left already the complete network had changed, the initial "rectangle" already become a single street with some arms connecting the entrances/exits. We suppose that this is due to the faster change at the beginning.

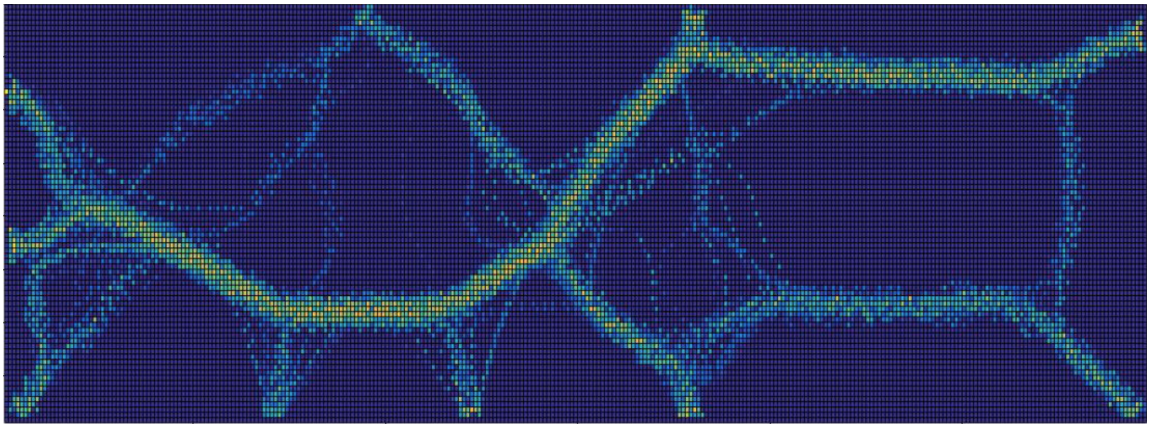

Figure 14: Simulation on Joyce Park after 5000 iterations

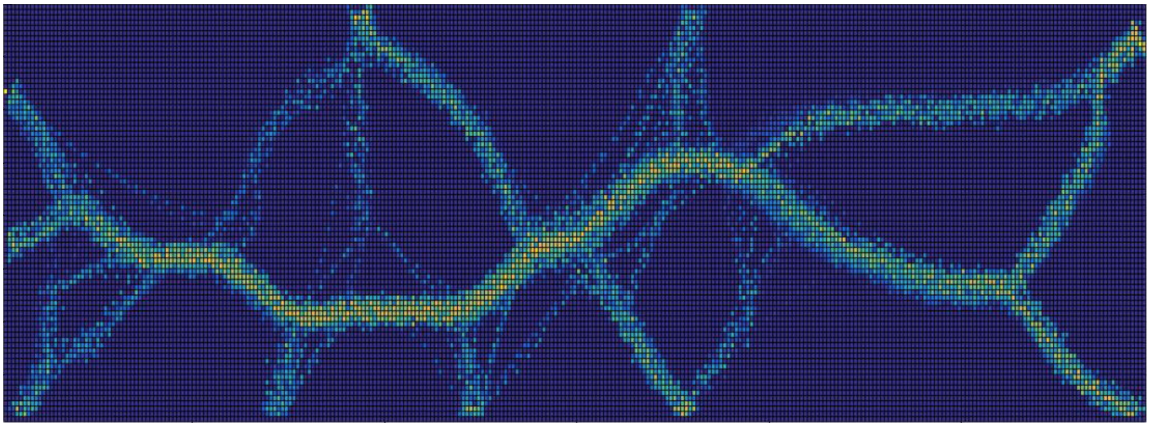

Figure 15: Simulation on Joyce Park after 7000 iterations

Going to the end, also on the right side the streets changed to one single big street with the links to entrances/exits. The only change till the end is only the "triangle" on the right of the park, that closes to a single crossing.

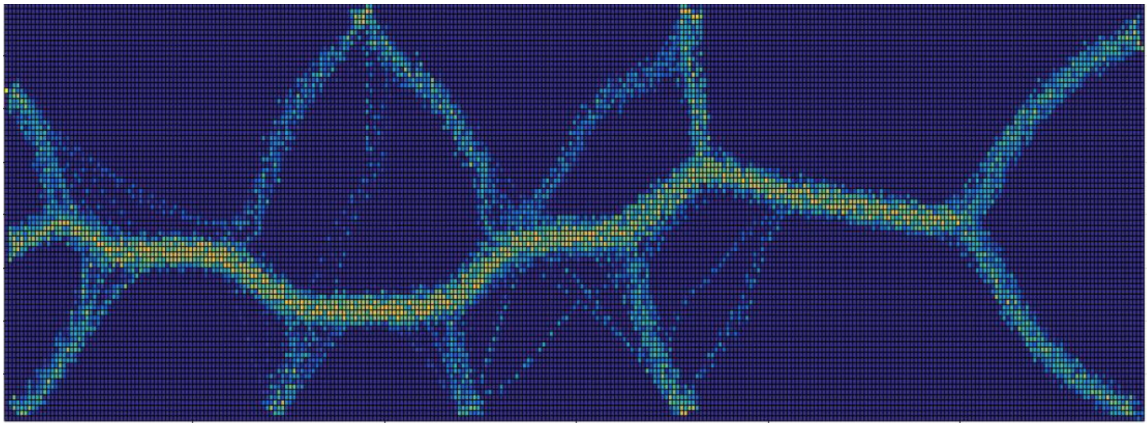

Figure 16: Simulation on Joyce Park at the end

How we can see in the video at the end the network is stable and there is no modification in the last $2'000$ iterations. However there are still some peoples walking across the park without following the present trails. We think that this behavior is realistic since also in a real park not all peoples follow the trails, but crosses the green areas.

7 Summary and Outlook

The work for this project was extremely interesting at the beginning, we had a lot of fun implementing our model and trying to find solutions to the problems. However going to the end, while waiting that the computer performed all the simulations, it became a little bit boring.

During our work, we encountered a lot of difficulties, some of them are listed below:

- We had some problems implementing the code that compute the potential of the ground.
- Solved the first problem our model become very slow, we partially solved it by adding some "if" in order to avoid useless calculus, although it remained slow. The last simulation took almost a week to perform. That was the factor which did not allow us to make another simulation.

The target of an ongoing project could be to make the model more realistic and faster. There are a lot of possibilities to achieve this goal. Some suggestions:

- Reanalyze our model of the topology and improve it
- To take into account that on certain areas of a park can not be walked on
- Implement also a "social-force" model. It would so be able to simulate also the behavior of peoples in the case that there is a high concentration of pedestrians.

For sure further interesting results could be made by simply changing some parameters and finding data about the percentage of pedestrians entering and going out by the single entrance/exit.

8 References

References

[1] Modelling Evolution of Human Trail Systems - Dirk Helbing 1997.

[2] Camazin 2001 - chapter 13

A Code

A.1 'start.m'

```
1
2  %................................................
3  %.................First simulation..................
4  %................................................
5
6  clear;
7  clc;
8  N=1; % Number of simulation
9
10 %......... Dimension of matrix
11
12 dm = 50; % x dimension
13 dn = 50; % y dimension
14
15 %......... Initial ground condition
16
17 G1 = zeros(dm,dn); % Topology
18
19 G2 = zeros(dm,dn); % Initial trails
20 % load ('Trail_1.mat'); % If you want initial presence of trails
21 % G2=Trail_1;
22
23 %.......... Entrance and exits
24
25 num_ent=4; % Number of entrance/exits (min N=1 ; max N=4)
26
27 % Coordinate have to be between 1 and dm for x, 1 and dn for y
28
29 E1v = [1,1]; % Coordinates entrance 1
30 E2v = [1,49]; % Coordinates entrance 2
31 E3v = [49,49]; % Coordinates entrance 3
32 E4v = [49,1]; % Coordinates entrance 4
33
34 U1v = [1,1]; % Coordinates exit 1
35 U2v = [1,49]; % Coordinates exit 2
36 U3v = [49,49]; % Coordinates exit 3
37 U4v = [49,1]; % Coordinates exit 4
38
39 %.......... Parameters
40
41 R = 0.5; % regeneration ratio
42 I = 30; % Intensity of footprints
43 v = 3; % Velocity
44 l=0.8; % Parameter of direction
```

```
sigma = 4; % Visibility
iter= 2000; % Number of iteration
dt = 0.1; % Unit of time

%.......... Save video and final trails

video_name='Quadrato_1__I30-si4-l0.8-it2000.avi'; % Video name
trail_name='Quadrato_1__I30-si4-l0.8-it2000.mat'; % Name of the final ...
    matrix of trails

main % start simulation



%..................................................
%.................Second simulation.................
%..................................................

clear;
clc;
N=2; % Number of simulation

%......... Dimension of matrix

dm = 70; % x dimension
dn = 70; % y dimension

%......... Initial ground condition

G1 = zeros(dm,dn); % Topology

G2 = zeros(dm,dn); % Initial trails
% load ('Trail_1.mat'); % If you want initial presence of trails
% G2=Trail_1;

%.......... Entrance and exits

num_ent=4; % Number of entrance/exits (min N=1 ; max N=4)

% Coordinate have to be between 1 and dm for x, 1 and dn for y

E1v = [35,70]; % Coordinates entrance 1
E2v = [35,1]; % Coordinates entrance 2
E3v = [1,35]; % Coordinates entrance 3
E4v = [70,35]; % Coordinates entrance 4

U1v = [35,70]; % Coordinates exit 1
U2v = [35,1]; % Coordinates exit 2
U3v = [1,35]; % Coordinates exit 3
U4v = [70,35]; % Coordinates exit 4
```

```
94
95 %.......... Parameters
96
97 R = 0.5; % regeneration ratio
98 I = 10; % Intensity of footprints
99 v = 3; % Velocity
100 l=0.8; % Parameter of direction
101 sigma = 4; % Visibility
102 iter= 2000; % Number of iteration
103 dt = 0.1; % Unit of time
104
105 %........... Save video and final trails
106
107 video_name='Quadrato_2__I10-si4-l0.8-it2000.avi'; % Video name
108 trail_name='Quadrato_2__I10-si4-l0.8-it2000.mat'; % Name of the final ...
    matrix of trails
109
110 main % start simulation
111
112 %................................................
113 %.................Third simulation.................
114 %................................................
115
116 clear;
117 clc;
118 N=3; % Number of simulation
119
120 %......... Dimension of matrix
121
122 dm = 70; % x dimension
123 dn = 70; % y dimension
124
125 %......... Initial ground condition
126
127 G1 = zeros(dm,dn); % Topology
128
129 G2 = zeros(dm,dn); % Initial trails
130 % load ('Trail_1.mat'); % If you want initial presence of trails
131 % G2=Trail_1;
132
133 %.......... Entrance and exits
134
135 num_ent=3; % Number of entrance/exits (min N=1 ; max N=4)
136
137 % Coordinate have to be between 1 and dm for x, 1 and dn for y
138
139 E1v = [2,70]; % Coordinates entrance 1
140 E2v = [2,1]; % Coordinates entrance 2
141 E3v = [70,35]; % Coordinates entrance 3
142 E4v = [90,45]; % Coordinates entrance 4
```

```
143
144 U1v = [2,70]; % Coordinates exit 1
145 U2v = [2,1]; % Coordinates exit 2
146 U3v = [70,35]; % Coordinates exit 3
147 U4v = [90,45]; % Coordinates exit 4
148
149 %.......... Parameters
150
151 R = 0.5; % regeneration ratio
152 I = 30; % Intensity of footprints
153 v = 3; % Velocity
154 l=0.8; % Parameter of direction
155 sigma = 4; % Visibility
156 iter= 2000; % Number of iteration
157 dt = 0.1; % Unit of time
158
159 %........... Save video and final trails
160
161 video_name='Triangolo_1__I10-si4-l0.8-it2000.avi'; % Video name
162 trail_name='Triangolo_1__I10-si4-l0.8-it2000.mat'; % Name of the final ...
        matrix of trails
163
164 main % start simulation
165
166 %................................................
167 %................Fourth simulation...............
168 %................................................
169
170 clear;
171 clc;
172 N=4; % Number of simulation
173
174 %......... Dimension of matrix
175
176 dm = 70; % x dimension
177 dn = 70; % y dimension
178
179 %......... Initial ground condition
180
181 G1 = zeros(dm,dn); % Topology
182
183 G2 = zeros(dm,dn); % Initial trails
184 % load ('Trail_1.mat'); % If you want initial presence of trails
185 % G2=Trail_1;
186
187 %.......... Entrance and exits
188
189 num_ent=2; % Number of entrance/exits (min N=1 ; max N=4)
190
191 % Coordinate have to be between 1 and dm for x, 1 and dn for y
```

```
192
193 E1v = [1,25]; % Coordinates entrance 1
194 E2v = [1,45]; % Coordinates entrance 2
195 E3v = [1,45]; % Coordinates entrance 3
196 E4v = [90,45]; % Coordinates entrance 4
197
198 U1v = [90,45]; % Coordinates exit 1
199 U2v = [90,25]; % Coordinates exit 2
200 U3v = [1,45]; % Coordinates exit 3
201 U4v = [90,45]; % Coordinates exit 4
202
203 %.......... Parameters
204
205 R = 0.5; % regeneration ratio
206 I = 10; % Intensity of footprints
207 v = 3; % Velocity
208 l=0.8; % Parameter of direction
209 sigma = 4; % Visibility
210 iter= 2000; % Number of iteration
211 dt = 0.1; % Unit of time
212
213 %.......... Save video and final trails
214
215 video_name='Parallele_1__I10-si4-l0.8-it2000.avi'; % Video name
216 trail_name='Parallele_1__I10-si4-l0.8-it2000.mat'; % Name of the final ...
       matrix of trails
217
218 main % start simulation
```

A.2 'main.m'

```
1  G3 = zeros(dm,dn); % presence of peoples
2  G4 = zeros(dm,dn); % potenzial of ground
3  G5 = zeros(dm,dn); % slope of ground
4  M(:,:,1) = G1;
5  M(:,:,2) = G2;
6  M(:,:,3) = G3;
7  M(:,:,4) = G4;
8  M(:,:,5) = G5;
9
10 E = zeros(dm,dn); % entrance
11 E(E1v(1),E1v(2))=1;
12 E(E2v(1),E2v(2))=1;
13 E(E3v(1),E3v(2))=1;
14 E(E4v(1),E4v(2))=1;
15
16 U = zeros(dm,dn); % exits
```

```
U(U1v(1),U1v(2))=1;
U(U2v(1),U2v(2))=1;
U(U3v(1),U3v(2))=1;
U(U4v(1),U4v(2))=1;

num_per=0; % Number of peoples

fig = figure('Position',[100 1 1200 900]);


vidObj = VideoWriter(video_name);
open(vidObj);

for i=2:iter

    change_ground; %modify ground

    if(mod(i,4)==2) %insert peoples
        if (num_ent==1)
            insert_person_1_entrance_1_exit;
        end
        if (num_ent==2)
            insert_person_2_entrance_2_exit;
        end
        if (num_ent==3)
            insert_person_3_entrance_3_exit;
        end
        if (num_ent==4)
            insert_person_4_entrance_4_exit;
        end
    end

    direction_pend; % calculate best direction
    move_person; % moves peoples

    hold off;
    surf(M(:,:,2))
    view(2)
    currFrame = getframe;   % Write each frame to the file.
    writeVideo(vidObj,currFrame);
    [N,i]
end

close(vidObj); % Close the file.
close all
PR1 = M(:,:,2);
save (trail_name,'PR1');
```

A.3 'change_ground.m'

```
for j=1:dm
    for k=1:dn
        if(M(j,k,3) == 1) % if there is a person
            dG = -R*M(j,k,2)*dt + I*(1 - M(j,k,2))*dt;
            M(j,k,2) = M(j,k,2) + dt*dG;
        else
            dG = -R*M(j,k,2)*dt;
            M(j,k,2) = M(j,k,2) + dt*dG;
        end
    end
end
```

A.4 'insert_person_1_entrance_1_exit.m'

```
num_per= num_per +1;

M(E1v(1),E1v(2),3)=1;
P(num_per,:)=[E1v(1),E1v(2),U1v(1),U1v(2),0];
```

A.5 'insert_person_2_entrance_2_exit.m'

```
h = rand;
o = rand;
num_per= num_per +1;

if (h<=0.5) %Entrance 1
    M(E1v(1),E1v(2),3)=1;
    P(num_per,:)=[E1v(1),E1v(2),U2v(1),U2v(2),0]; %Exit 2
end

if (h>0.5) %Entrance 2
    M(E2v(1),E2v(2),3)=1;
    P(num_per,:)=[E2v(1),E2v(2),U1v(1),U1v(2),0]; %Exit 1
end
```

A.6 'insert_person_3_entrance_3_exit.m'

```
h = rand;
o = rand;
num_per= num_per +1;

if (h<=0.33) %Entrance 1
    M(E1v(1),E1v(2),3)=1;
    if (o<=0.5) %Exit 2
        P(num_per,:)=[E1v(1),E1v(2),U2v(1),U2v(2),0];
    end
    if (o>0.5) %Exit 3
        P(num_per,:)=[E1v(1),E1v(2),U3v(1),U3v(2),0];
    end
end

if (h>0.33 && h<=0.66) %Entrance 2
    M(E2v(1),E2v(2),3)=1;
    if (o<0.5) %Exit 1
        P(num_per,:)=[E2v(1),E2v(2),U1v(1),U1v(2),0];
    end
    if (o>=0.5) %Exit 3
        P(num_per,:)=[E2v(1),E2v(2),U3v(1),U3v(2),0];
    end
end

if (h>0.66) %Entrance 3
    M(E3v(1),E3v(2),3)=1;
    if (o<=0.5) %Exit 1
        P(num_per,:)=[E3v(1),E3v(2),U1v(1),U1v(2),0];
    end
    if (o>0.5) %Exit 2
        P(num_per,:)=[E3v(1),E3v(2),U2v(1),U2v(2),0];
    end
end
```

A.7 'insert_person_4_entrance_4_exit.m'

```
h = rand;
o = rand;
num_per= num_per +1;

if (h<=0.25) %Entrance 1
    M(E1v(1),E1v(2),3)=1;
    if (o<=0.33) %Exit 2
        P(num_per,:)=[E1v(1),E1v(2),U2v(1),U2v(2),0];
    end
    if (o>0.33 && o<=0.66) %Exit 3
```

```
11          P(num_per,:)=[E1v(1),E1v(2),U3v(1),U3v(2),0];
12      end
13      if (o>0.66) %Exit 4
14          P(num_per,:)=[E1v(1),E1v(2),U4v(1),U4v(2),0];
15      end
16  end
17
18
19  if (h>0.25 && h<=0.5) %Entrance 2
20      M(E2v(1),E2v(2),3)=1;
21      if (o<=0.33) %Exit 1
22          P(num_per,:)=[E2v(1),E2v(2),U1v(1),U1v(2),0];
23      end
24      if (o>0.33 && o<=0.66) %Exit 3
25          P(num_per,:)=[E2v(1),E2v(2),U3v(1),U3v(2),0];
26      end
27      if (o>0.66) %Exit 4
28          P(num_per,:)=[E2v(1),E2v(2),U4v(1),U4v(2),0];
29      end
30  end
31
32  if (h>0.5 && h<=0.75) %Entrance 3
33      M(E3v(1),E3v(2),3)=1;
34      if (o<=0.33) %Exit 1
35          P(num_per,:)=[E3v(1),E3v(2),U1v(1),U1v(2),0];
36      end
37      if (o>0.33 && o<=0.66) %Exit 2
38          P(num_per,:)=[E3v(1),E3v(2),U2v(1),U2v(2),0];
39      end
40      if (o>0.66) %Exit 4
41          P(num_per,:)=[E3v(1),E3v(2),U4v(1),U4v(2),0];
42      end
43  end
44
45  if (h>0.75) %Entrance 4
46      M(E4v(1),E4v(2),3)=1;
47      if (o<=0.33) %Exit 1
48          P(num_per,:)=[E4v(1),E4v(2),U1v(1),U1v(2),0];
49      end
50      if (o>0.33 && o<=0.66) %Exit 2
51          P(num_per,:)=[E4v(1),E4v(2),U2v(1),U2v(2),0];
52      end
53      if (o>0.66) %Exit 3
54          P(num_per,:)=[E4v(1),E4v(2),U3v(1),U3v(2),0];
55      end
56  end
```

A.8 'move_person.m'

```
for n=1:num_per
     if(P(n,5)==0)
        vrand = (rand + 0.5)*v;
        sx = round(ealfa(n,1)*vrand);
        sy = round(ealfa(n,2)*vrand);
        M(P(n,1),P(n,2),3) = 0;
        if ((P(n,1) + sx)>= dm || (P(n,2) + sy)>= dn || (P(n,1) + sx)<= ...
            1  || (P(n,2) + sy)<=1)
             M(P(n,1),P(n,2),3) = 0;
             clearvars P(n);
             P(n,5)=1;
        else
             P(n,1) = P(n,1) + sx;
             P(n,2) = P(n,2) + sy;
        end

        M((P(n,1)),(P(n,2)),3) = 1;
     else
         M(P(n,1),P(n,2),3) = 0;
     end
end
```

A.9 'direction_pend.m'

```

for aa=1 : dm   % for that goes trough the matrix
    for bb=1:dn
        pottot=0; %sum of all potential with respect to point [aa bb]
        for q=1:dm
            for w=1:dn
                if (M(q,w,2)~=0)
                    pot = M(q,w,2)*exp(-((aa-q)^2 + ...
                        (bb-w)^2)^(1/2)/sigma);%potential of the ground ...
                        in [q w] respect to [aa bb]
                    pottot=pottot+ pot; %sum of all potentials
                end
            end
        end
        pottot = pottot/(dm*dn); %avarage
        M(aa,bb,4)=pottot; %putting the potential in the matrix crated ...
            for it
    end
end

for n=1:num_per  % for all peoples
    if (P(n,5)==0)  % peoples that are not "cancelled"
```

```
20
21          pot_per = M(:,:,4);
22
23          for q=1:dm
24              for w=1:dn
25                  dist = ((P(n,1)-q)^2 + (P(n,2)-w)^2)^(1/2); %distance
26                  if (dist ~=0)
27                      pend = (1000*M(q,w,1) - M(P(n,1),P(n,2),1))/dist; %slope
28                      if (pend < 0)
29                          pot_per(q,w) = M(q,w,4) - exp(1/pend);
30                      elseif (pend > 0)
31                          pot_per(q,w) = M(q,w,4) - exp(-1/pend);
32                      else
33                          pot_per(q,w) = M(q,w,4);
34                      end
35                  else
36                      pot_per(q,w) = M(q,w,4);
37                  end
38              end
39          end
40
41          [fy,fx]=gradient(pot_per(:,:));  % gradient of the potential matrix
42
43          gradnorm = ((fx(P(n,1),P(n,2)))^2 + (fy(P(n,1),P(n,2)))^2)^(1/2);
44
45          distmeta=((P(n,3) - P(n,1))^2 + (P(n,4) - P(n,2))^2)^(1/2); ...
                %distance from target
46
47          if (distmeta >=1)
48
49              if (gradnorm ~= 0)
50                  ex = (P(n,3) - P(n,1))/distmeta + ...
                        fx(P(n,1),P(n,2))*1/gradnorm;
51                  ey = (P(n,4) - P(n,2))/distmeta + ...
                        fy(P(n,1),P(n,2))*1/gradnorm;
52              else
53                  ex = (P(n,3) - P(n,1))/distmeta;
54                  ey = (P(n,4) - P(n,2))/distmeta;
55              end
56              norm = (ex^2 + ey^2)^(1/2);
57          else
58              M(P(n,1),P(n,2),3) = 0;
59              clearvars P(n);
60              P(n,5)=1;
61          end
62          ealfa(n,:) = [ex/norm,ey/norm]; % direction vector
63      end
64  end
```