An Agent-Based Simulation Model for Pedestrian Unidirectional Movement

Robson dos S. França   Maria das Graças B. Marietto   Wallace R. de Santana
Guiou Kobayashi
Universidade Federal do ABC - Santo André, SP - Brazil
{robson.franca,graca.marietto,wallace.santana,guiou.kobayashi}@ufabc.edu.br

Abstract

Pedestrian Movement behavior can be analyzed in different ways. One of the most common approaches for this subject is the Cellular Automata. However, the pedestrian behavior is usually modeled by a reactive-response framework. Also, the pedestrians are treated as just numbers or elements in a grid. This paper proposes a basic framework for a multi-agent pedestrian movement model. Applying the same rules found in a Cellular-Automata-reactive model, this framework allows a new look for this kind of phenomenon, and it paves the ground for a more cognitive agent model and a physical environment with distinct features as well.

1 Introduction

In big cities the population growth demands new investments in transport, and consequently further studies about how people move across those environments. As one of the most critical components in transport systems, the pedestrian movement needs to be studied in order to help the decision-making process in dealing with elements such as traffic flow, signaling design and others that must be designed to ensure users' safety and comfort in public places like theaters, train stations, stadiums, among others.

However, there are fewer models for pedestrian flow than for vehicle flow [3, 8, 11]. This could be partially explained because pedestrian movement is a chaotic and complex process without rigid rules. On the other hand, vehicles have their movement guided by well-defined rules regarding lane-changing, overtaking and speed limits.

This paper develops a model for pedestrian movement in an environment with obstacles, based on Cellular Automata (CA) and Multiagent-Systems (MAS), using Multiagent Simulations theories and technologies. In this context, pedestrians and obstacles are MAS, and a CA model is used for agents' interaction in a local level, along with the pedestrians' temporal evolution and dissemination of their behavior in the environment.

Cellular Automata (CA) are discreet dynamic systems formed by entities occupying cells, whose behavior at each step of the simulation is defined by local rules [12]. CA models are advised for simulating dynamic process and complex systems. In transportation systems' modeling CA has been used to simulate vehicles' and pedestrians' flow [7, 9].

The movement of a pedestrian group can be modeled like a MAS because they both have similar characteristics, such as: (i) they are open systems - pedestrians can enter or leave the simulation scenario and the system will not require restarting, (ii) each pedestrian/agent action affects the society subsequent actions, forming an intricate connection network, (iii) the pedestrian movement is socially constructed, and occurs by surging, emerging behaviors, (iv) they present a high degree of unpredictability in the decision-making process.

A multiagent simulation model allows the study of how pedestrian movement occurs in certain situations, capturing the essential elements of this phenomenon in a controlled artificial environment. This feature is important because making these experiences in a real situation usually is prohibitive, it could generate life-threatening risks or it could have an exorbitant economical cost.

In order to evaluate the unidirectional movement pedestrian multiagent model, a case study based on modeling and simulation-based analysis of Estação da Luz is shown. Estação da Luz is a subway station and it is part of the São Paulo City subway system in Brazil. The simulations' scenario analyzes critical performance indicators like pedestrian average speed, traffic flow, available space for movement and pedestrian density.

In [1] the authors applied Cellular Automata for modeling a unidirectional pedestrian flow. That model captured efficiently the behavior of pedestrians at micro level. Also, a formation of aggregated structures (patterns) could be noticed, and they emerged from the agents interactions at macro level.

The model was developed based on authors' former tech-

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nical knowledge of vehicle traffic and the observation of security videos at subway stations. Using rules present in vehicle traffic, the [1] proposal was verifying how these rules could work in pedestrian flows. The usage of CA allowed the replication of chaotic behavior of pedestrians.

The simulation developed in this paper is based on the [1] works, since (i) it adopts the same rules that set the pedestrian unidirectional movement, and (ii) uses CA to model a pedestrian movement in a 2D environment. However, this paper extends [1]'s results with three contributions.

This paper's first contribution is the insertion of obstacles in the simulation scenarios. The behavior analysis of pedestrian confronted with obstacles is important because it occurs in real life, like at subway and train stations, emergency exits, sidewalks, etc. For this paper, to allow the pedestrian to contour obstacles, some rules were changed from the original model (see Section 2.1). A pixel map was chosen to describe the obstacles' arrangement.

The second contribution is the use of Multiagent System's theory in the model's development. The obstacles and pedestrians are represented as autonomous agents, where each one is located in a grid cell. The pedestrian agents have their own local rules, which define their movements in an environment with obstacles. These rules, combined with agents' interaction, allow modeling and observing the emerging behavior of pedestrian movement at micro and macro level.

The development of a multiagent simulation, our third contribution to [1]'s work, is motivated by the chance of making a relation between individual entities and a program, which leads to the creation of an artificial world formed by interactive computational entities [4]. This allows a definition of agents and its relations in a customized way, narrowing the gap between the actual system and the simulation. In addition, the structure of MAS in simulation is proper for modeling and understanding some of the elements related to social interaction which occurs in pedestrian movement, such as coordination, intentionality, free will and resolution of conflicts [6].

2 Proposed Model

At first, this model mimics Adler & Blue cellular automata model described in [1]. If the model behaves in a similar fashion than Adler & Blue model, we might assume that our model follows the same concept. Therefore, Adler & Blue model could be used as a static validation for this proposed model [2]. Also, Adler & Blue model was validated according to the Highway Capacity Manual, which is one of the greatest references for traffic, vehicle and pedestrian movement.

From this point, the model could be extended in many ways. For instance, a cognitive approach using a reinforcement learning algorithm could be easily applied. That way, the agent found in the resulting model will no longer act in a reactive-response chain. Instead, he will observe the environment and quickly communicate with other agents, forming his own beliefs. All the agents will have a specific goal: to get to his destination as fast as possible, which could be called a "desire". Finally, by observing and analyzing the best routes, the agent will take the best lanes and move towards his target, and that will be his intention [5].

2.1 Model Rules

The local rules are performed in two stages. In the first stage it is established whether the pedestrian will (or will not) change to another lane. After that, based on the lane change, the agent rules will establish how many cells the agent will move forward. This amount of cells will define the agent's speed ($step(p_n)$).

2.1.1 Lane-Changing Rules

Four rules are employed to decide the pedestrians' movement regarding the change of lanes. The first two rules establish if the nearby cells can be occupied by the pedestrian in a lane-changing condition. Once established if there are free nearby cells, the rules three and four are applied in order to move the pedestrian to a lane, or keep it in the current lane. Tables 1 and 2 shows these rules.

Table 1. *Rules for Lane Changing*

Rule 1:	This rule establishes if the right lane or the left lane is occupied or not. In order to accept that a lane is free, the next adjacent lane is analyzed so the possibility that two pedestrians could go, in the same interaction, to the same lane is avoided. **IF** the immediately left/right lane is beyond the grid limit **OR** the immediately left/right cell is occupied by another pedestrian or obstacle **OR** the immediately left/right cell is free but the two-lane-distant left/right cell belongs to the grid and it is occupied by a pedestrian **THEN** set that left/right cell as occupied
Rule 2:	**IF** the immediately right cell is set as occupied (according to Rule 1) **AND** the immediately left cell is set as occupied (according to Rule 1) **THEN** keep pedestrian on his current lane **ELSE** execute Rule 3

Table 2. *Rules for Lane Changing*

Rule 3:	Once it is defined that one or two adjacent lanes are free, the rules 3 and 4 are used to establish which lane the pedestrian will go **IF** there is just one lane which its free space ahead is the longest of all of the free lanes **THEN** move the pedestrian to that lane
Rule 4:	If there are two or more lanes with the same free space ahead (and that free space is the longest), apply one of the following rules
Rule 4a:	A tie with all lanes If there are three lanes with the same free space ahead, pick one of the lanes randomly applying a probability of 80% for the current lane and 10% for each one of the adjacent lanes. That implies that the pedestrian tends to stay on the current lane in the case of a tie with all free adjacent lanes
Rule 4b:	A tie with the adjacent lanes **IF** there are two adjacent lanes with the same free space ahead **THEN** pick one lane randomly using a 50%/50% probability for the adjacent lanes
Rule 4c:	A tie with the current lane and one of the adjacent lanes **IF** there is one adjacent lane with same free space ahead of the current lane **THEN** determine randomly the lane-changing using a 50%/50% probability for the adjacent lane and the current lane

2.2 Moving Forward Rule

The next rule establishes how many cells the pedestrian will move forward. The maximum number of cells that pedestrian p_n can advance will be the lowest value between $v_{max}(p_n)$ and $step(p_n)$. However, before moving forward, the environment must be updated with the choices set in the previous rules. After that, when each pedestrian is going to establish the number of cells to go forward, he will take the possible pedestrians in front of him into consideration in order to make his decision. Table 3 shows this rule.

Table 3. *Rules for Movement*

Rule 5:	**IF** the current free space ahead is less or equal than the pedestrian p_n's maximum speed **THEN** set pedestrian speed $v(p_n) = step(p_n)$ **ELSE** set pedestrian speed $v(p_n) = v_{max}(p_n)$

The multiagent model proposed in this work was employed in a case study regarding Estação da Luz, a subway station in São Paulo city, Brazil. In order to analyze Estação da Luz, a model and a simulation were built, and the simulation's results were checked.

Estação da Luz is a multi-modal station that connects the suburban train system - which covers many cities of Great São Paulo metropolitan area - with São Paulo City's subway system. It was chosen as the simulation subject because of the large flow of passengers (40,000 per hour, at rush hours), and the great amount of passageways with a unidirectional pedestrian movement. The case study was set on a passageway located in a junction point that links the subway station and Pinacoteca do Estado de São Paulo (art museum). This passageway is 54.6 meters (179 feet) long and there are some obstacles like turnstiles and columns.

For this study, the multi-agent simulation was implemented in the Swarm platform [10]. The pedestrian can move from south to north, and he is not allowed to move through other pedestrians, or to occupy the same space (cell). The pedestrian also moves in a circular fashion, which means that when a pedestrian exits the lattice on the north, he will appear on the other side (south) heading the same direction (south-north). Each agent is placed in a CA cell, in a bi-dimensional grid of 45 by 95 cells. Each cell represents a square which has one size of 1.5 feet, and an area of 2.25 square feet.

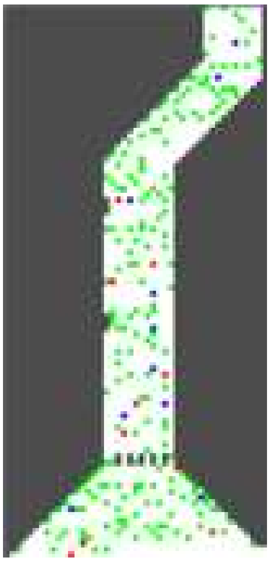
At the beginning of the simulation, the quantity of free cells without obstacles that is available is counted (F). After that, the density d is defined (which $0.05 <= d <= 0.95$), and $N = \lfloor d \times F \rfloor$ pedestrians are created and randomly distributed on the lattice. With a rounded (periodical) grid, the amount of pedestrians remains the same during the whole simulation, with a constant density of $d = \frac{N}{F}$.

The pedestrians have the same set of local rules, but a different $v_{max}(p_n)$ is defined for each one of them. Following the same division found at [1], the pedestrians are classified into one of these categories:

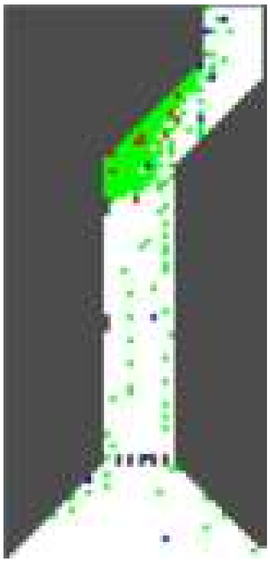
- Pedestrians with $v_{max}(p_n)$ = 2 cells/time step (or 3 feet/s). In the simulation they are represented as blue dots;
- Pedestrians with $v_{max}(p_n)$ = 3 cells/time step (or 4.5 feet/s). In the simulation they are represented as green dots;
- Pedestrians with $v_{max}(p_n)$ = 4 cells/time step (or 6 feet/s). In the simulation they are represented as red dots.

3 Simulation

The Figure 1(a) shows a Swarm simulation at initial state, when the simulated pedestrians are randomly placed. Each colored dot is a simulated pedestrian, and the black dots are the obstacles. The Figure 1(b) shows an end-result



(a) 2D Map Initial State (0.15 density)



(b) 2D Map Final State (0.15 density)

Figure 1. Lattice During Simulation (0.15 density)

from a simulation experiment (see next section), when lanes have been formed.

The pedestrians' distribution in the lattice follows [1]'s work, which 90% of pedestrians have $v_{max}(p_n)$ = 3 cells per time-step, 5% have $v_{max}(p_n)$ = 2 cells per time-step and 5% have $v_{max}(p_n)$ = 4 cells per time-step. This distribution is important because if there was just one speed for all pedestrians, an overcrowding would happen and the final spatial distribution would hinder the formation of new lanes. According to [1], the proposed speed distribution also aims for optimization of pedestrians' speed.

In the case study, the simulation dealt with 19 scenarios, and the density was incremented by 0.05 steps after each scenario. The first scenario started with $d = 0.05$ and the last one started with $d = 0.95$. Each scenario was executed 10 times, and each simulation had 11 thousand steps. The first thousand steps were discarded because they were transients required just for the simulation stability. Each step related to one real time second, resulting in 2.78 hours ($10,000s \approx 2.78h$) of pedestrians' flow at Estação da Luz.

The following variables had their average values calculated from 10 simulations for each scenario:

Density

This variable is considered in two forms: relative and absolute density. The relative density is the proportion of the quantity of pedestrians and the quantity of free spaces ($d = \frac{N}{F}$). It describes how the lattice is filled, representing the average count of occupied cells. The absolute density is the quantity of pedestrians divided by the free area, measured in square feet. The conversion between these two forms is made dividing the relative density by the area of each cell (i.e., 2.25 sq. ft), $d_{abs} = \frac{d_{rel}}{2.25}$. For example, a relative density of 0.15 corresponds to an absolute density of 0.067 pedestrians per sq. ft. That implies that each pedestrian has 15 square feet available to move on the lattice if the relative density is 0.15.

Average Speed

It represents how many cells, on average, each pedestrian moved in a simulation time-step. This value is calculated by summing the number of steps of each pedestrian at each time-step, and then dividing the calculated sum by the number of pedestrians.

Traffic Flow

The traffic flow shows how many pedestrians crossed, on average, one specific line on the environment along the entire execution of the simulation. For all scenarios studied by this work, the line was in the northernmost limit (superior) of the lattice.

Space

The space is the reciprocal of density, i.e., it is the proportion of the quantity of free spaces on the lattice and the number of pedestrians ($S = \frac{F}{N}$). It shows how many free spaces are available for each pedestrian, on average, in the simulation.

4 Conclusions

This paper proposes a unidirectional pedestrian movement model based on Multiagent Systems (MAS) and Cellular Automata (CA) main concepts. The multiagent approach enables an intelligent-driven behavior in the decision-making process, which brings the model and the simulation closer to reality, and running in a controlled environment poses as an extra feature. The multiagent-based approach is very promising for simulation of pedestrian movement because it makes possible to simulate abnormal and panic situations and their effects on traffic without imposing risks for human beings. Through these simulations architects, traffic planners and designers involved on pedestrian movement could study and develop optimized solutions.

A multiagent-based simulation was developed in order to aid with the validation analysis. This simulation was validated in two steps. At first the model proposed by [1] was implemented, and so far the results found were consistent with their work, which proves that the agents move according to the authors' unidirectional proposal. After that first validation, a case study was implemented, based on Estação da Luz subway station, located in São Paulo city, Brazil. The validation applied here was of a static / structural type [2], in order to establish if the model's structure and inner-working fit the closest possible into the target system. There was no comparison of the simulation resulting data with real data since there is no historical data, publicly available, about the station's pedestrian movement. However the results are promising and they seem close to the actual pedestrian movement behavior.

Future research will focus on making the pedestrian agent more flexible, in order to be able to deduce new movement rules, to build ontologies and to share that information to the other agents. For instance, in a panic situation, agents could move in different ways, taking their experiences and situational goals into consideration. Also, an agent could learn how to move by the most efficient way possible, and that learning could happen along with the simulation.

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