Proceeding Series of the Brazilian Society of Computational and Applied Mathematics, v. 7, n. 1, 2020.

Trabalho apresentado no XXXIX CNMAC, Uberlândia - MG, 2019.

Proceeding Series of the Brazilian Society of Computational and Applied Mathematics

A fire elitist cellular automaton-based model to verify pedestrian flow simulated in real environments using Arduino

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Resumo. Safety in crowded environments needs attention by public authorities. If the structure of an environment offers danger when a crowd tries to escape in time of an accident, there is always the risk of someone getting hurt. Computational models and simulations from these abstractions are important for determine the confidence level and security of a building structure. The application of cellular automata in the computational simulation is justified by their high powerful parallel computational tool. The main objective of this paper is the proposition of a cellular automata based model for the pedestrian evacuation in the fire environments. The proposed mathematical model was compared to a real simulation using an Arduino control for counting the pedestrian evacuation time. The comparison between the proposed model and its precursor shows that our model best mimics the real evacuation simulation, because of the non-deterministic parameter that was added herein[2].
Palavras-chave. Cellular Automata, Simulation Model, Fire Propagation, Evacuation.

1 Introdução

The study of pedestrian dynamics has been investigated nowadays since humans, or any other animal species, forms agglomerations of different purposes by living in societies. Thus, strategies must ensure the safety of each agent into the buildings, in traffic or in any environment where crowd formation can occur [1]. For example, if a fire occurs in the environment it represents an extreme risk factor to the crowd, thus evacuation time is a prime factor in ensuring the health and physical integrity of the individuals involved in the accident.

In this work, the cellular automata (CA) are used to simulate the evacuation process of pedestrians in a fire environment, called herein as Fire Elitist Cellular-Automaton Pedestrian (FECAP) model. The main characteristics of the two-dimensional model proposed by [2] was preserved, as well as some characteristics of the precursor models [3–5]. The fire model proposed was based on CA model [6]. To evaluate the CA computational suggested

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[2]The authors thank CNPq, CAPES, FAPEMIG and PROPI IFTM for financial support.

model an Arduino was used. We programmed Arduino to measure the pedestrian flux in simulations near the exit, without fire. Besides that, tests in different situations were performed, allowing the investigation of its applicability.

2 Proposed model

The evacuation model proposed herein is based in [2,3], and considers three main steps. The first step considers the creation of a floor field, where each CA grid cell x_{ij}, using CA Moore's neighborhood with radius ($r = 1$), that corresponds to an integer and positive value guiding the pedestrian in the cell choice towards the exit. The second step is the creation of a new CA rules set that defines the pedestrians movement [7]. Finally, the third stage consists of the CA rules for fire spreading based in [6] precursor model.

2.1 Floor Field

The building structure representation is two-dimensional structure. Each floor cell to be simulated receives an assignment with integer and positive values. The assignment of cells weights follows the algorithm proposed by [2] - similar to Euclidian distance. This strategy assigns a smaller weight near to the exits and as the pedestrian moves away we have a higher floor field. The walls and fire cells are considered by the pedestrian an obstacle, he must move away from the obstacles to exit from room.

2.2 Pedestrian movement

In the lattice, the panic factor [2] will be considered only when the pedestrian encounters an intense fire cell or even when two pedestrians have the same movement intention (just one is selected), unlike the [3] model. Another major difference is that near the nests the cell choice strategy is different from [3] where authors adopted a deterministic movement. In this work, when the pedestrians are close to the exits, they choose the cell based on an elitist non-deterministic choice - where the remaining cells, even if they are not the small ones, have a possibility of being chosen. This elitist probabilistic movement developed herein prevents: lines formation near the nests [2], jamming [8], inertial behavior [5], and permits alternative path [3] choices.

1. To calculate the route, a pedestrian signals the cell that he wants to move in neighborhood. If there is more than one pedestrian with the same cell choice, only one performs the movement. With this, the path of all pedestrians is calculated.

2. The process of deciding the movement is an elitist probabilistic function, where the pedestrian chooses with high probability the shortest distance cells. The other cells are chosen using low probability values.

   (a) The neighborhood identification process assigns values c_{ij} to each cell. If a cell has the lowest value in the neighborhood, the $c_{\max}$ value is assigned to the cell.

(b) On the other hand, if the cell does not have the lowest value, then the $c_{\min}$ value is assigned to the cell. Each cell has a c_{ij} probability to be chosen from a total $\sum_{ij=0}^{m} c_{ij}$, that represents the sum of all values c_{ij} in the CA neighborhood.

(c) The Equation 1 represents the probability decision [4] function $P(x_{ij})$. After the cell decision process, the pedestrian moves to another cell in its neighborhood.

$$P(x_{ij})^{t+1} = \begin{cases} \frac{c_{\max}}{\sum_{ij=0}^{m} c_{ij}} & \leftarrow x_{ij}^{t} \leq \forall x_{ij} \in \eta_{x_{ij}}^{m} \\ \frac{c_{\min}}{\sum_{ij=0}^{m} c_{ij}} & \leftarrow x_{ij}^{t} > \forall x_{ij} \in \eta_{x_{ij}}^{m} \end{cases} \tag{1}$$

3. If the pedestrian route is in the same direction of the fire focus, the pedestrian calculates a closer route where there is no intense fire state.

4. If an individual reaches the door, he is eliminated to let others leave as well.

5. Steps (1), (2), (3) and (4) are repeated until all pedestrians are evacuated.

2.3 Fire propagation model

The fire propagation rule is based on the CA model [6], but in our model wind was not considered. Fire propagation cells will use the same principles of pedestrian movement rules. However, at each time step - that the mesh is updated - the previous state of the fire will continue to be saved together with the current state, thus generating the fire propagation. In this work, four states are considered for the CA cells affected by fire, red (■): where the focus is located; orange (■) and light orange (■): cell that is powerfully burning; yellow (■): burning cell. In red state is created the focus φ of the fire which is more intense. In the following times the possibilities of fire spread are probabilistically smaller, considering different shades of colors: red, orange, light orange and yellow. The fire has a probability 30% from propagates fire according to [6] model.

2.4 Arduino flux control model

Arduino is an open source computer hardware and software company, in our work, we used the Ultrasonic Sensor HC-SR04 component that was connected in Arduino to allows us to read distances up to 80 centimeters with 3 millimeters of accurate. It was positioned in the door exit and used simply to measure the distance between the sensor and a pedestrian (student living from a classroom) during a real simulation and the time that each pedestrian passed near the door. The Real Time Clock (RTC) component allows the real-time recording in which each pedestrian passed through the door. The simulation was used to check the output flow near the exit door of a 5×6 meter classroom that represents a classroom with $N = 20$ students held at the institution where the authors carry out the research project. The objective of the real simulation is to design an approximation between the mathematical model based on cellular automata proposed herein and the behavior pedestrian model in real evacuation, in this case, without fire considering.

3 Experimental results

The experiments presented in this section were compiled using the standard C programming language and were divided into two parts: the first deals with the preliminary tests for behavior update rule validation; and the second one represents the temporal analysis that statistically compares the spread propagation time and pedestrians living time. The FECAP model was configured using $c_{\min} = 1$, $c_{\max} = 10$, only when the pedestrians number is $N \geq 10$ and $x_{ij} \leq 3$ (near the door exit), that the elitist model probability is used. It is an important investigation due to with less then 10, the jamming factor not alter the simulation process.

3.1 Visual analysis of the simulation model

Initially, Figure 1 shows some experiments were carried out to verify the patterns formation, fire spread evolution and all pedestrians evacuation in the 11×17 cells environment. Results should be read from top to bottom, from left to right. Initially, there are

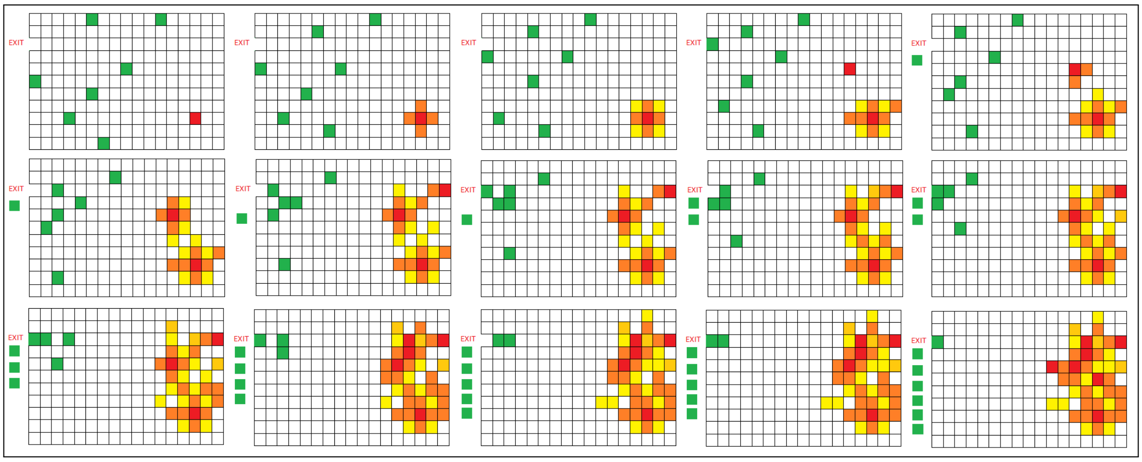

Figura 1: Snapshots of CA model during $T = \{1, 2, 3, \cdots, 15\}$ steps, where, red ■, orange ■, light orange ■, yellow ■ are fire spread, ■ are pedestrians, and □ are cells.

$N = 7$ pedestrians in the room with one fire focus ($\varphi = 1$). The focus trigger of the fire spread, and each pedestrian moves one cell toward the exit according to Equation 1. The fire intensity decreases, according to the 4 states of the burned cell [6], the pedestrians walk without conflict. At each time step, a new fire spot is inserted into the grid; the first pedestrian comes to the exit while the others continue to move. Subsequently, the fire continues to spread; the pedestrian steps away from the entrance to the exit to avoid conflicts. The fire continues to spread until remains a conflict between the pedestrians and the pedestrian from position a $x_{4,3}$ does not move because its adjacent cells are occupied and it can not go back because the cells have higher value and are closer to the fire. Another conflict is observed: the pedestrian $x_{4,1}$ does not move because its adjacent cells are occupied and it can not go back because the cells have higher value and are closer to

DOI: 10.5540/03.2020.007.01.0338

the fire. Further, the pedestrian of cell $x_{3,2}$ does not move because its adjacent cells are occupied and it can not go back due to the cells have higher value and are nearer to the fire. All other iterations, the fire continues to spread and the pedestrians cross the exit without conflicts and agglomerations until all pedestrians are evacuated.

3.2 Statistical analysis evacuation time

To validate the model proposed herein, from the mathematical and statistical point of view, some simulations were performed with pedestrians varying from $N = \{1, 2, 3, 5, 7, 10, 15, 20, 30\}$, using a lattice of 20×30 cells. For each N, 100 simulations were carried out, the average and median of each of N were calculated using only one fire focus in the room. In addition, the confidence interval calculated for the mean is 95% of accuracy. Figure 2 indicates that the mean values for T increase as the number of pedestrians increases. To compare our FECAP evacuation model with the evacuation model proposed in [3],

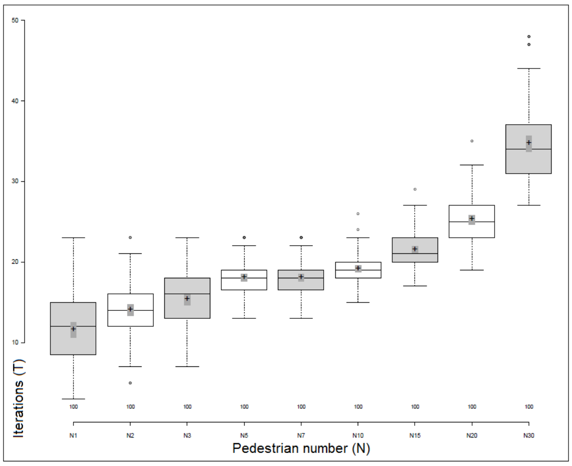

Figura 2: Boxplots: 100 simulations using $N = \{1, 2, 3, 5, 7, 10, 15, 20, 30\}$ pedestrians with their respective: means ⊞, medians ⊟ and 95% of confidence intervals ■ are presented.

a data chart was presented and then the regression was performed to make the learning curve for T, based on mean's values ($\bar{x_1}$ and $\bar{x_2}$), as the number N of pedestrians increases. Figure 3 shows green points representing our proposed elitist model for evacuation and the blue points represent the [3] evacuation movement model. The blue line represents the [3] growth curve for the number steps T prediction as the value of N increases and the next number of iterations can be predicted using the Equation 2.

$$y_1 = 1.7758726 \times \bar{x_1} + 0.499 \tag{2}$$

The green line represents our FECAP movement model growth curve for the prediction of the number of steps T as the value of N increases and the next number of iterations can be predicted using the Equation 3.

$$y_2 = 1.253783 \times \bar{x_2} + 0.201 \tag{3}$$

DOI: 10.5540/03.2020.007.01.0338

It is possible to observe in Figure 3 that our model relatively requires more steps to achieve complete all pedestrian evacuation, since, the model is similar to the real simulation used an Arduino to real pedestrian (20 students) flux counting near the exit.

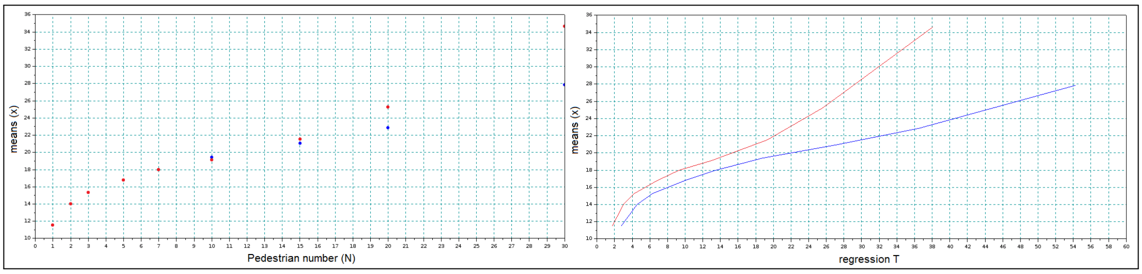

Figura 3: Comparisons between the precursor model (fire focus $\varphi = 1$). Left: the scatter plot which ■ represents Castro and Lima [3] model and ■ represents FECAP model. Right: lines represent the linear regression using Equations 2 and 3 respectively.

3.3 Real simulation using Arduino

The actual simulation consists in a room of size 5×6 with $N = 20$ students by placing the ultrasonic Arduino model is represented, in left of Figure 4, and Arduino sensor is positioned front of the exit. At each step a pedestrian evacuation was recorded by the Arduino RCT component, middle of Figure 4. This evacuation model was contrasted with the models proposed in [3] and FECAP model. Figure 4 - at right - shows in the x-axis the time each of the $N = \{1, 2, 3, \cdots, 20\}$ pedestrians passing through the ultrasonic sensor, while the y-axis represents pedestrian performs the evacuation. Authors [3] preserved the linear deterministic model of [2] and it is possible to perceive a linear evacuation [3], different from the real simulation. FECAP model, on the other hand, creates a realistic simulation, avoiding lines formation near the exits, linear queues formation during evacuation is not common, since in case of panic, the models tend to follow a non-linear behavior. Therefore, the probabilistic model with an elitist choice movement, proposed herein, is closer of a pedestrian behavior in a real evacuation simulation.

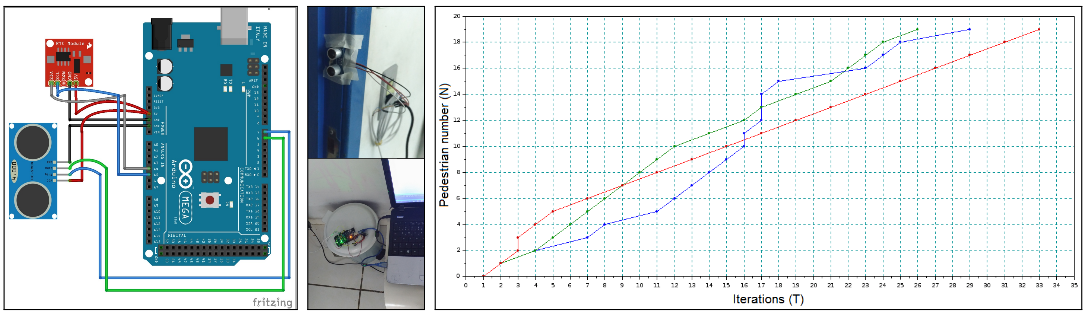

Figura 4: Left: Arduino model. Middle: Arduino constructed. Right: Comparisons between 3 models using the ■ real, ■ Castro and Lima [3] and ■ FECAP simulations.

4 Conclusions and future work

From the simulations of described model it was possible to generate visual data, where standard pedestrian evacuation behaviors and the fire spreading dynamics could be observed. In addition, statistical data were obtained by relating the average iterations to the different amounts of pedestrians, which indicates that the increase in pedestrians always leads to an increase in time iterations. The great advantage of using the model developed here is that it is flexible for the parameters input, like the fire focus or the distance for elitist calculus, already adopted and other parameters can be inserted. Besides that, a controller was developed in Arduino to show that the cellular-automaton discrete model proposed herein is more realistic than the previous one, because of the linearity of pedestrians near exits [2]. The computational simulation alone can not guarantee a hundred percent of reliability to the model, but, it begin an analysis that can be deepened in a later research paper performing more real simulations using Arduino platform.

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