Using an Agent-Based Cellular Automaton for Emergency Evacuation Simulation

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Abstract. We consider a simulation-based approach to address crowd evacuation problems. An agent-based cellular automaton model is used to model the environment and the collective behavior of the crowd, taking into account both rational decision-making and social interaction. We have developed an interactive visualization tool that is used to provide a demonstration of the use of this model and show how it can be used to capture different qualitative crowd behaviors.

Keywords: Crowd Evacuation · Agent-based System · Cellular Automaton · Floor Field

1 Introduction

Some studies indicate that most of our lives are spent indoors, be it for work, leisure, or transportation [10]. This makes it immediately clear that having emergency plans for safely evacuating indoor areas in case of an emergency is crucially important. This is a complex matter into which many factors come into play. One of these is undoubtedly the behavior of the crowd should an emergency arise. For this purpose, simulation-based approaches provide an effective way to describe the evacuation behaviors of the crowd and predict the outcome of the evacuation process [3]. In essence, such approaches build upon a certain mathematical model of the crowd, but not as a closed mathematical expression but rather as a collection of equations or rules defining how the state of the crowd changes along time, and whose successive application will resemble at same level the crowd behavior when starting at some particular state.

The particulars of these models will depend on different factors, such as for example the granularity of the simulation (cf. [3,13]). Thus, we can have (i) macroscopic models in which the crowd is considered a fluid in a continuous medium (e.g.[1,8]), (ii) social force models in which the crowd is a collection of individual particles in a continuous space whose dynamics is controlled by their interaction among themselves and with the environment (e.g. [2,12]), and cellular automaton (CA) models in which the individuals live in a discrete space subject to local evolution rules (e.g. [14,16]). Each of these approaches provides a different trade-off between two conflicting objectives, namely simplicity and realism (see [3,7,11] for more details), and CA models are arguably appealing for their comprehensibility and power to capture emergent behaviors.

We have previously defined a probabilistic agent-based CA model for crowd behavior that integrates a rational escape strategy and crowd aversion behavior that can be used within a simulation-based optimization framework [4,5,6]. In this work, we present a demonstration of the functioning of this model and how it can be used to capture different crowd behaviors and describe a tool to visualize the actual results.

2 Main Purpose

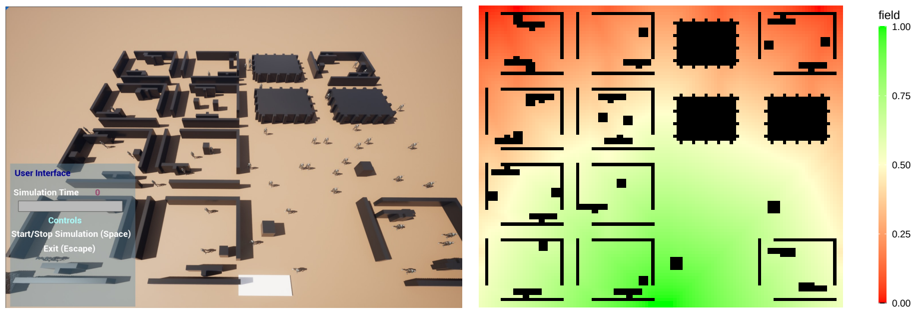
This demonstration is aimed at showing how the model devised can produce realistic evacuation behaviors from arbitrary indoor environments (represented as enclosed spaces in whose interior a collection of obstacles is laid out –such a layout is meant to capture the properties of real-world environments as shown later on– and in which evacuation exists are placed in desired locations).

Needless to say, the use of this model within a simulation-based optimization approach requires extracting statistics from the simulation to define metrics to maximize or minimize. It is at any rate important to have a visual description of the actual simulation in order to assess the truthfulness of the agents' behaviors. To this end, we have devised a tool that allows visualizing an arbitrary simulation (as given by a particular indoor scenario and the crowd behavior emanating from the particular parameterization of the model) using a video-game-like 3D user-interface.

3 Demonstration

We assume an indoor space populated by a collection of people referred to as *pedestrians*, and that will be represented by agents. these agents live within a CA, namely a discrete and dynamic system that consists of a grid of cells, each of which can have a finite number of states. These states (and some additional associated information) are instrumental in defining the structural properties of the environment and in describing snapshots of the system state at any given moment. More precisely, there are three states, namely *blocked* (cells mapping to obstacles in the environmental model), *empty* (cells representing traversable space) and *occupied* (non-blocked cells that are currently occupied by an agent). Time goes by in discrete time steps, and in each of them agents make decisions about what to do in order to escape from the environment.

The behavior of agents is determined by several internal parameters that model both physical properties of the pedestrian (i.e., the speed at which they can move, which can be different for each agent) and their psychological profile (capturing features such as rationality and fear to overcrowding). The former translates quite straightforwardly into the simulation, by using the maximum



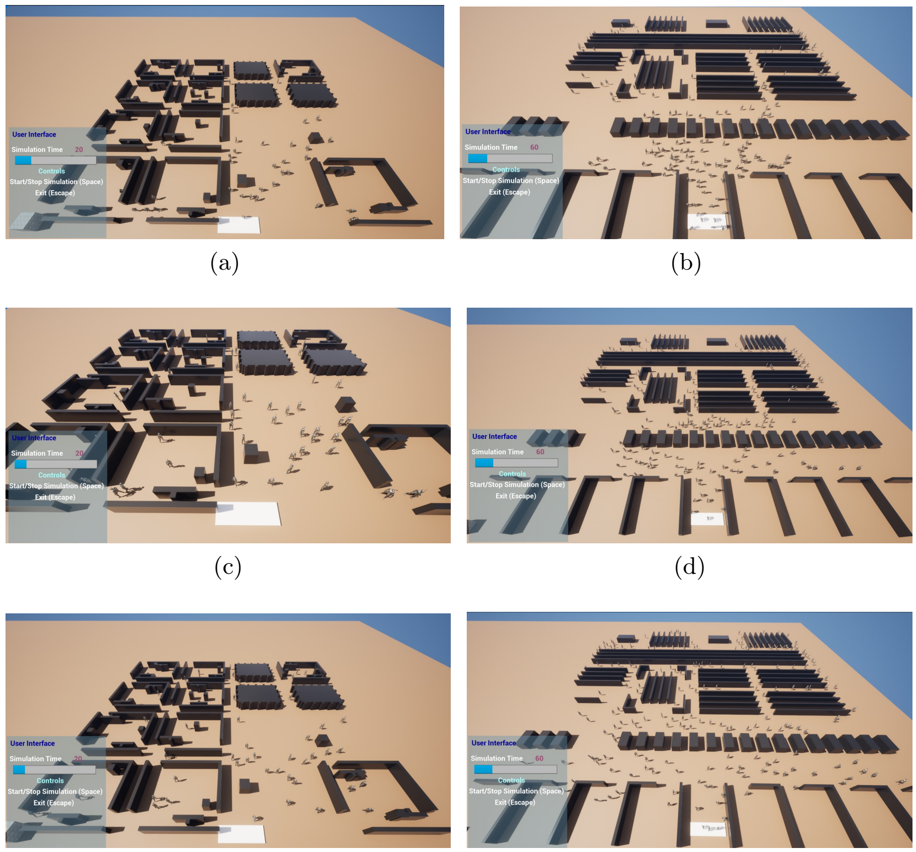
(a) (b)

Fig. 1: (a) Visualization of an office environment. There is an exit in the middle of the bottom wall. (b) Corresponding static attraction field. Larger values indicate stronger attraction of the corresponding position

available speed to define the length of simulation time steps (relating this maximum speed to the size of cells in the grid) and having agents move only with probability proportional to the ratio between their own speed and this maximum speed. As to the psychological parameters, they rest on two fields that are defined on the grid, a *static attraction field* $\mathcal{A}$ (providing information on the closeness of each cell to the nearest exit – see Fig. 1 for an example), and a *dynamic repulsion field* $\mathcal{R}$ (providing information on how limited movement would be in a certain cell, given both the layout of obstacles and the positions of other nearby agents). We refer to [6] for the mathematical details of the computation of each of these fields. Each agent has two parameters ϕ, ψ respectively called *attraction* bias and *repulsion* bias, that are used to weight the contribution of each field into a single numerical *desirability* measure. Subsequently, the agents (following a random sweep policy) move to an empty cell in their Moore neighborhood, with probability proportional to the excess desirability to each cell with respect to the worst accessible neighbor. This sensitivity to differential desirability is consistent with observed cognitive responses [15].

The particular parameterization ϕ, ψ can be used to model different behaviors. Thus, larger values of ϕ can be used to capture more rational behavior because agents will adhere more intensely to the shortest path available to get to an exit from their current location. In contrast, ψ captures the cautiousness and social distancing of pedestrians. Therefore, higher values of ψ will correlate with increased anxiety induced by enochlophobia. Thus, having $\psi > 0$ results in an increasingly disordered evacuation, as shown in Fig. 2 for two different environments respectively resembling an office floor and a supermarket. Notice how as the ϕ/ψ balance tilts towards the latter, the crowd ceases to follow definite evacuation paths and start to scatter around the environment[3].

[3] Some videos of these simulations are available at https://bit.ly/Bio4Res.



(a) (b) (c) (d) (e) (f)

Fig. 2: Snapshots of the system state in an office environment at $t = 20$s (left column), and in a supermarket environment at $t = 60$s (right column) starting from the same initial crowd distribution ($n = 50$ agents for the office environment, and $n = 200$ agents for the supermarket environment). From top to bottom: (a)(d) $\phi = 4, \psi = 0$ (e)(b) $\phi = 2, \psi = 0.25$ (c)(f) $\phi = 1, \psi = 0.5$.

To enhance the visualization of our simulations, we have developed an interactive application utilizing Unreal Engine 5. This tool allows for visualizing diverse environments and managing multiple simulations. Users can effortlessly initiate or pause simulations at will, switch camera perspectives in real-time during experiments, and track individuals within each simulation, thanks to a unique identifier assigned to them (that is, showing the simulation in third person or in first person). This level of interactivity and control provides an immersive experience, enabling detailed observation and analysis of the simulated scenarios.

4 Conclusions

This work has provided a demonstration of the usefulness of agent-based CA models of pedestrians to simulate evacuation from indoor environments. An interactive visualization tool has been devised. This tool does not only illustrate the functioning of the model, but it is also very important to study and characterize the behavior of the model, allowing both a better understanding of the underlying mechanics of the system, as well as a calibration of its parameters with respect to the qualitative crowd model intended. We continue to work on enriching the underlying model and developing more powerful simheuristics [9] to exploit this model in simulation-based optimization settings.

Supplementary Materials. The interested reader may find the source code of our model in our GitHub repository[4] and data files describing different environments in our OSF data repository[5].

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References

1. Bellomo, N., Bellouquid, A., Knopoff, D.: From the Microscale to Collective Crowd Dynamics. Multiscale Modeling & Simulation **11**(3), 943–963 (Jan 2013)
2. Cao, R.F., Lee, E.W.M., Xie, W., Gao, D.L., Chen, Q., Yuen, A.C.Y., Yeoh, G.H., Yuen, R.K.K.: Development of an agent-based indoor evacuation model for local fire risks analysis. Journal of Safety Science and Resilience **4**(1), 75–92 (Mar 2023)
3. Chen, J., Shi, T., Li, N.: Pedestrian evacuation simulation in indoor emergency situations: Approaches, models and tools. Safety Science **142**, 105378 (2021)
4. Cotta, C.: Navigating the aisles: Evolutionary algorithms for supermarket evacuation planning. In: Genetic and Evolutionary Computation Conference (GECCO '24 Companion). pp. 89–90. ACM, New York, NY (2024)
5. Cotta, C.: Optimization-driven workplace evacuation using evolutionary algorithms and derivative-free methods. In: 8th International Conference on Intelligent Systems, Metaheuristics & Swarm Intelligence. pp. 86–91. ACM, New York, NY (2024)
6. Cotta, C., Gallardo, J.: Evolutionary algorithms for optimizing emergency exit placement in indoor environments. In: Smith, S., Correia, J., Cintrano, C. (eds.) Applications of Evolutionary Computation – EvoApplications 2024. Lecture Notes in Computer Science, vol. 14634, pp. 194–208. Springer, Cham (2024)

[4] https://github.com/Bio4Res/pedestrian-evacuation-optimization
[5] https://osf.io/cnh7u/

7. Dong, H., Zhou, M., Wang, Q., Yang, X., Wang, F.Y.: State-of-the-Art Pedestrian and Evacuation Dynamics. IEEE Transactions on Intelligent Transportation Systems **21**(5), 1849–1866 (May 2020)
8. Golas, A., Narain, R., Lin, M.C.: Continuum modeling of crowd turbulence. Physical Review E **90**(4), 042816 (Oct 2014)
9. Juan, A., et al.: A review of simheuristics: Extending metaheuristics to deal with stochastic combinatorial optimization problems. Operations Research Perspectives **2**, 62–72 (Dec 2015)
10. Klepeis, N.E., Nelson, W.C., Ott, W.R., Robinson, J.P., Tsang, A.M., Switzer, P., Behar, J.V., Hern, S.C., Engelmann, W.H.: The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. Journal of Exposure Science & Environmental Epidemiology **11**(3), 231–252 (2001)
11. Kouskoulis, G., Spyropoulou, I., Antoniou, C.: Pedestrian simulation: Theoretical models vs. data driven techniques. International Journal of Transportation Science and Technology **7**(4), 241–253 (Dec 2018)
12. Li, Z., Xu, C., Bian, Z.: A force-driven model for passenger evacuation in bus fires. Physica A: Statistical Mechanics and its Applications **589**, 126591 (Mar 2022)
13. Martinez-Gil, F., Lozano, M., García-Fernández, I., Fernández, F.: Modeling, Evaluation, and Scale on Artificial Pedestrians: A Literature Review. ACM Computing Surveys **50**(5), 72:1–72:35 (Sep 2017)
14. Shi, M., Lee, E.W.M., Ma, Y.: A dynamic impatience-determined cellular automata model for evacuation dynamics. Simulation Modelling Practice and Theory **94**, 367–378 (Jul 2019)
15. Somervail, R., et al.: Waves of Change: Brain Sensitivity to Differential, not Absolute, Stimulus Intensity is Conserved Across Humans and Rats. Cerebral Cortex **31**(2), 949–960 (10 2020)
16. Zheng, Y., Li, X.G., Jia, B., Jiang, R.: Simulation of pedestrians' evacuation dynamics with underground flood spreading based on cellular automaton. Simulation Modelling Practice and Theory **94**, 149–161 (Jul 2019)