Physica A 451 (2016) 135–148

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

An improved Cellular Automata model to simulate the behavior of high density crowd and validation by experimental data

Claudio Feliciani [a,*], Katsuhiro Nishinari [a,b]

[a] *Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan*

[b] *Department of Aeronautics and Astronautics, Graduate School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

HIGHLIGHTS

- The model developed allows using Cellular Automata for high density crowd.
- The numerical model was validated using empirical data from a real-world scenario.
- Deadlock formation has been studied in detail using the data obtained from simulation.
- The framework developed can be extended to different areas such as granular matter.

ARTICLE INFO

Article history:
Received 1 September 2015
Received in revised form 18 December 2015
Available online 1 February 2016

Keywords:
Bidirectional pedestrian flow
Cellular Automata
Fundamental diagram
Simulation
Deadlock formation

ABSTRACT

In this article we present an improved version of the Cellular Automata floor field model making use of a sub-mesh system to increase the maximum density allowed during simulation and reproduce phenomena observed in dense crowds. In order to calibrate the model's parameters and to validate it we used data obtained from an empirical observation of bidirectional pedestrian flow. A good agreement was found between numerical simulation and experimental data and, in particular, the double outflow peak observed during the formation of deadlocks could be reproduced in numerical simulations, thus allowing the analysis of deadlock formation and dissolution. Finally, we used the developed high density model to compute the flow-ratio dependent fundamental diagram of bidirectional flow, demonstrating the instability of balanced flow and predicting the bidirectional flow behavior at very high densities. The model we presented here can be used to prevent dense crowd accidents in the future and to investigate the dynamics of the accidents which already occurred in the past. Additionally, fields such as granular and active matter physics may benefit from the developed framework to study different collective phenomena.

1. Introduction

Dynamic of human crowds exhibits many mysterious and fascinating aspects which have attracted researchers of several disciplines. In particular, the processes leading to the occurrence of accidents in dense crowd are still not completely understood and ways to prevent those situations are mostly summarized as general guidelines and generic constructional norms.

---

[*] Corresponding author.
E-mail address: feliciani@jamology.rcast.u-tokyo.ac.jp (C. Feliciani).

http://dx.doi.org/10.1016/j.physa.2016.01.057
0378-4371/

Studies on the dynamic of human crowds stretch many decades back, but it is only in the last decades that researchers have focused on computer simulations to predict the behavior of pedestrians in a vast range of scenarios. Motivation for the use of numerical simulation lies in the fact that it is possible to study scenarios which could not be reproduced experimentally, either because of the risks related to potential injuries or because of the difficulties arising in hiring a large number of participants during supervised experiments (in order to obtain significant experimental data several hundred people are required, but reported studies usually employed few hundred or even less participants [1–4], while simulations can deal with several thousand people).

Most of the models used for dense crowd are based on physical principles, with granular and active matter physics having the largest contribution [5–7]. In some case (especially when the crowd is not extremely dense) fluid-dynamic was found being accurate enough to describe macroscopic pedestrian motion. In addition, statistical mechanics and theories based on many-body systems have been useful to understand the characteristics of crowds composed of a large number of people. In this regard, research on pedestrians dynamic has a mutual relationship with research on collective phenomena, with discoveries in both disciplines contributing to the overall understanding.

In particular, because of the difficulties arising in obtaining realistic data during supervised experiments (considering that participants are aware that an experiment is being carried out) and the privacy concerns related with the use of public surveillance cameras for empirical observations, granular matter physics has been useful in gaining precious experimental evidence of different situations; especially in the case of evacuation through a narrow exit [8–11].

However, granular matter physics is not always directly comparable with human crowd. Therefore, considering the above reasons, research on extreme scenarios (deadlock, bottlenecks, accidents, panic outbreak, ...) has been mostly focused on two directions: computer simulations and research involving animals, which enable to reproduce dangerous scenarios while minimizing the ethical and juridical concerns (in this context experiments have been reported using different sort of animals [12–15]).

Numerical models used in computer simulations can be divided into continuous and discrete models (although different categorization criteria may be considered). To the former ones belong the fluid-dynamic methods [16–18] and the social force model [19,20]. Among discrete models, multi-agent systems [21–23] and Cellular Automata (CA) [24–26] are the most widely used.

In some cases simulation models were validated using realistic empirical data gained from supervised experiments under low densities. In particular previous experimental research has dealt with bidirectional counter-flow [2,4,27], cross-flow at intersections and evacuation through an exit door [28,29].

In this study we will focus on the CA model, because of its simplicity and its capability to easily include behaviors observed on pedestrians in real situations. CA has proven being a powerful tool to describe collective pedestrian behavior in many scenarios and its relative simplicity and the limited number of rules implemented in it allows very short computational time. Various phenomena observed in reality could be described using CA models, including the arching at the exit door [30], lane formation [31] and the faster-is-slower effect [32]. However, because of the constraints imposed by the use of a discrete mesh, special models had to be developed to overcome some of the limitations. In this frame a real-coded lattice gas model [33] was derived to improve the accuracy of diagonal motion, a force field was added to assess the potential danger in a dense crowd [34], different velocities were included to account for the velocity distribution usually observed in pedestrians [35,36] and a finer mesh was proposed to increase the spatial accuracy [25].

However, CA has still the limitation of allowing simulation only for a limited density, namely the one imposed by the size of its mesh, typically set at 0.4 m × 0.4 m [37]. When each cell of the model has been filled, the maximum density allowed by CA is reached. In general, the mesh used in CA models is sufficient for simulating most of the scenarios observed in pedestrian crowds. In particular, free-flow is accurately modeled and lane formation observed in reality is reproduced in simulation with satisfactory accuracy. On the other hand, in congested situations, local densities may go beyond the limit imposed by the CA mesh. Densities up to 8.4 persons m^{-2} have been reported [38] in controlled experiments (under safe conditions), implying that higher densities (possibly higher than 10 persons m^{-2}) can be observed in panicking crowds resulting in injuries or death.

In this study we present a sub-mesh implementation of the CA model which increases the mobility of the pedestrians in dense crowd, thus allowing the simulation of highly congested scenarios. Different sub-mesh approaches have been reported in relation with the Boltzmann lattice used in fluid-dynamic [39–41], but the method reported here represents a new approach which enables to overcome the low-density limits imposed by the use of the standard discrete mesh in CA.

In order to validate the model we compared the simulation results with experimental data obtained during morning rush hour in a crowded subway station in central Tokyo.

Given the interdisciplinary approach used, applications of the model presented here go beyond the field of pedestrians dynamics and granular matter physics in particular may benefit from it, especially for research related to phenomena like percolation, aggregation and diffusion.

2. Model description

In the case of pedestrian bidirectional flow, the use of a discrete mesh in CA models results in a limited mobility for colliding pedestrians. As a consequence, even at low flows, a complete stop may be observed when pedestrians coming from both directions encounter [42]. To avoid this problem, some authors proposed to introduce an exchange probability to