The Automatic Generation of an Efficient Floor Field for CA Simulations in Crowd Management

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Abstract. The Hermes project [1] demonstrated the usefulness of on site predictive simulations of probable evacuation scenarios for security personnel. However, the hardware needed was prohibitively expensive [2]. For use in crowd management, the software has to run on available computers. The CA methods, which are fast enough, have well known problems with treating corners and turns. The present paper shows how a standard CA method can be modified to produce a realistic movement of people around bends and obstacles by changing the standard floor field. This can be done adaptively allowing for the momentary situation using simple predictions for the immediate future. The approach has one or two tuning parameter that have an obvious meaning and can therefore be set correctly by people not familiar with the inner process of a CA simulation. With this, a high end laptop can simulate more than 100 000 persons faster than real time, which should be enough for most occasions. It is intended to integrate the method into the tool JuPedSim [23].

Keywords: Cellular automata · Modeling · Pedestrian dynamics Lanes at corners

1 Introduction

During the last few decades, the number and size of events that involve large crowds has increased considerably. At the same time, the safety requirements have increased also. Since about 1990, computer simulations have been established as a useful planning tool for the design of pedestrian facilities and are routinely applied in the design of large buildings, cruise ships, sports arenas or public transport facilities. However, the methods have not yet found their way into the steering of actual events, as the established systems for planning are too time consuming for steering of events, where simulation and display of results faster than real time is required. Faster and easier to use simulations can be helpful for crowd managers of large events, but also in the evacuation of facilities because of present danger (e.g. fire, bomb threat) where the preplanned

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evacuation routes may not be operational any more. The Hermes project demonstrated that on the site predictive simulations of probable crowd movement are feasible and useful for crowd management. However, the requirements in specific hardware were higher than facilities are willing to pay by a large margin.

Computer simulations of pedestrian facilities can be (and are) done on different scales. The coarsest scale uses a tree or network of pathways that take time, but have no active capacity restriction, and nodes (doors, junction of floors etc.), that do have active capacity restrictions [7]. These models are very fast, but there is no reliable way to include the highly nonlinear effects that appear in high density crowds. They may indicate that there is trouble ahead, but at that time (which is the time when information is needed most) they stop to make useful predictions. An intermediate scale is mostly handled by a cellular automata (CA) model where space and time are discrete and agents are moving from one space element to another according to some transition rules [11,15]. These methods are fast enough for on site real time simulations e.g. of a large sports stadium, and they can make predictions for high density crowds, but have in the established versions other deficiencies [16]. We will treat the details in the paper. The finest scale uses models in continuous space and time where agents are moved usually according to Newton's laws, by forces generated mostly internally as a reaction to the desired momentary destination and the local environment. Examples of this methods are [17,18]. It is possible to combine models on different scales [8–10], and this leads to a good combination of speed, resolution and reliability. Unfortunately, setting up the coupling is not automatic yet but requires expertise and time with predefined coupling zones, so this is at present not the way for crowd management.

In this paper we show how the most obvious problems of the standard CA can be removed by an automatic procedure with only a moderate increase in computing time. This modification is following the ideas of a manual changing of the floor field that the authors have implemented before [10,16] and demonstrated as reliable and useful. With this modification, a simple CA is able to simulate the movement of more than 100 000 persons faster than real time on an i7 quadcore for a large variety of floor plans. It still does not reach the flexibility and resolution of continuous models, and is not fully realistic in some aspects (more details below), but for a quick evaluation of the likely development of a situation over a few minutes it should be sufficiently accurate to be helpful.

2 General Properties of CA Models

Cellular automata are the most widely used approach. The commercial codes buildingEXODUS [12] and PedGo [13] are CA codes. They have demonstrated their ability to give good estimates of evacuation times of high rise buildings [19] or cruise ships, while details may still need improvement. While they differ in many aspects, the basics are identical.

2.1 Introduction to the General Theory

The principles of cellular automata for simulating pedestrians are explained in many places, e.g. [11,15]. For readability,we give a short sketch following [15]. The floor geometry is discretized into tiles, usually of 40 cm · 40 cm size. An initial distribution of persons on the tiles is defined. In every time step each person can move to another tile (or stay put) according to a probability depending on

- The availability of free space (only one person per tile at any time).
- A floor field describing the intended direction.
- Personal data, describing e.g. handicaps.

With a time step of ≈ 0.3 s this gives a reasonable speed of free movement of 1.3m/s.The movement is either done in parallel with subsequent conflict resolution or (simpler) in a random order sequentially. Non random orders have been used, but give strong artifacts. The floor field S is usually derived from the gradient of the distance to the destination (exit) in some metric, the Manhattan metric being the most common one because of its extreme simplicity.

Research codes may also use hexagonal tiles or smaller tiles with persons occupying more than one tile. They may also use more elaborate floor fields. These methods have somewhat different properties, but because they are not much in use they are not treated here.

2.2 Movement Properties of CA

The movement in simple CA grids is strongly non isotropic. Let us first consider the movement without interference from others towards a single cell goal. If for a person the direction to the goal is aligned with the grid, the movement probability is high (≈ 0.9) for that direction, small (≈ 0.03) for sidewards or no movement and almost nil for backward movement. If the direction is not aligned with the grid, the probability is ≈ 0.48 for the two grid directions that enclose the direction to the goal. For a grid aligned goal, this results in a very narrow path that is actually used. The probability to leave the direct path is low from the start, and when this has happened (on average once every 15 moves), the probability to get back to the direct path is almost 1/2 for every move, so a deviation of more than one grid cell from the direct path is extremely rare.

Table 1. Probabilities to pass through a cell for a oblique goal - top left to bottom right. The sum along each diagonal from top right to bottom left is 1.

1	$^1/_2$	$^1/_4$	$^1/_8$	$^1/_{16}$	$^1/_{32}$
$^1/_2$	$^2/_4$	$^3/_8$	$^4/_{16}$	$^5/_{32}$	$^7/_{64}$
$^1/_4$	$^3/_8$	$^6/_{16}$	$^{10}/_{32}$	$^{15}/_{64}$	$^{29}/_{128}$
$^1/_8$	$^5/_{16}$	$^{16}/_{32}$	$^{42}/_{64}$	$^{99}/_{128}$	1

The situation is quite different for a direction not aligned with the grid. For simplicity, we will at first consider only forward movements. There is equal probability of ≈ 0.5 to move right or left of the actual direction. This results in a spreading out of the likely positions to a binomial distribution to the right and left of the diagonal of the grid. This carries on until a position is reached where the direction is grid aligned. From here on, the movement is again concentrating along the direct Table 1. The small probability of no or backward movement changes the spreading of the path by a tiny margin only, it mostly introduces a retardation, the person usually just reaches the same position using more moves.

When the forward movement is blocked by another person, the most probable reaction is moving sidewards or not at all. This leads to a spreading out of the plumes in front of a narrow pathway or exit. Backward movement is always improbable. This means that there is no automatic redirection from a jammed exit to a open one at some distance.

2.3 Natural Structuring of the Space

By simply counting the high probability routes leading in and out of a cell, we can distinguish different types of grid cells. There are the special cells - exits cells, which can be entered, but not left via the normal mechanism, because a person in an exit cell is taken out of the simulation either immediately or after completion of a move, and possibly entrance cells, which can be left but not entered with CA. Beside these, we have three kinds:

– The normal cells, where there are as many high probability passes leading in as there are leading out
– The convergence cells, where there are more high probability passes leading in than there are leading out
– The divergence cells, where there are less high probability passes leading in than there are leading out.

The divergence cells build lines that separate the grid into areas with minimal or no interaction, because people are striving away. Usually, unless there are entrance cells on such a line, after very few moves these lines are completely empty. The convergence cells build lines which are possible points of trouble because they can be fed easier than emptied. This is especially true for cells where two convergence lines meet. Whether there will be trouble depends on the densities further out. The normal cells can be fed and emptied at the same speed, so they may be critical only when there are convergence cells close ahead. Figure 3 right shows such a division for a building that could e.g. be an exhibition room, and Fig. 3 left the number of persons usage of the grid cells for a simulation where 1795 persons are randomly distributed on the floor and walk to the exit with an ordering and timing so that there is no interference. It shows clearly the severe concentration on the convergence lines and the preference for $\approx 45^o$ to the grid when the direction is not aligned.

So there is a natural structure for the walking space: blocks defined by the convergence and divergence lines with a diagonal movement pattern inside, and

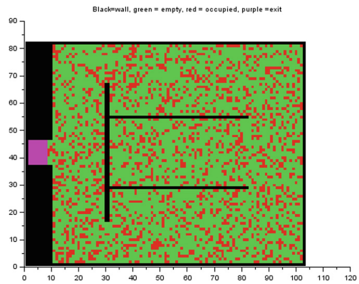

Fig. 1. Starting positions for all simulations. The size of the floor is 83 by 102 cells of $40 * 40\,\mathrm{cm}^2$

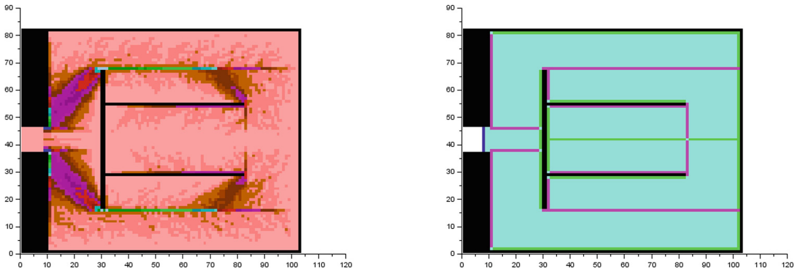

Fig. 2. Left: Utilization of tiles without conflicts (persons near exit start first, others wait till persons in front are out of reach), from pink–low (0-25) to green–high (>400) right: Exit (blue), walls (black) divergence lines (green) and convergence lines (purple) (Color figure online)

some blocks aligned with exits with parallel movement. The critical areas are near the crossing of two convergence lines. These are neighboring some of the corners or ends of the walls, other wall corners may be of no importance (Fig. 1).

3 Guiding People Around Corners

In actual walking, people are trying to cut corners only if that does not create conflicts with others. This results in the formation of lanes near the corner [14]. This can easily be modeled by changing the floor field near a corner in a way that not the shortest path is preferred but staying in lane [16]. The open questions are: How many lanes are needed, how long do they have to be and where exactly do they start and end. For use in crowd management, this needs an automatic procedure.

3.1 Getting the Required Number of Lanes

The number of lanes needed may be different for every corner and may change over simulation time. The easiest way to obtain the information is to run a simplified simulation - ignoring conflicts - and check the flow around each corner.

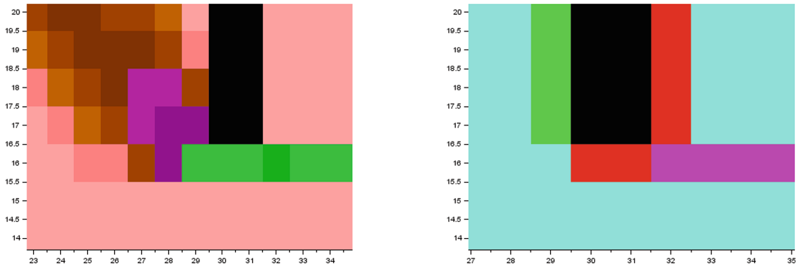

Fig. 3. Left: Utilization of tiles at corner of wall (black) without conflicts, from pink–low (0-25) to dark green – high (>600), right: divergence (green) and convergence (red/purple) lines. (Color figure online)

The maximal flow per lane is ≈ 1.5 persons/s, but this is modeling an uncomfortably crowded situation. Taking one lane for a flow of 1 p/s is usually better, but the factor should be a tuning parameter for the crowd manager to set. Multiple lanes may be required along walls and possibly (more below) along each side of an interior converging line. In the latter case, this line will often need to be moved outward so that its lanes do not end in a wall hugging lane that cannot take the flow.

With this, the computing time will be about twice the time for a simple CA simulation. In most cases, this is of no importance, CA is quite fast. For very large crowds, the time can be reduced by using the movement patterns described above. Any person can be moved to the next convergence line or along such a line to a corner in one action. This disregards the statistic spreading, but for the sum of many people moving, the spreading will cancel out to a large extent. The movement just along the most probable path will therefore be accurate enough to determine the expected flow, and reduce the computing time by a factor that depends on the distances between critical points. With this approximated simulation, the additional computing time will be dominated by the changing of the floor field.

It may be that the space available is not sufficient for the required number of lanes. This will result in an unavoidable jam in the final simulation, which will in all likelihood show up in reality just the same. The only thing that should be done is defining the lanes in a way that the load is approximately the same for all lanes, otherwise the simulation will perform worse than reality.

If the situation changes considerably over time, it may be advisable to gather and use information repeatedly. This will be treated below.

3.2 Placing the Lanes

At the forward end of a wall hugging convergence line the flux is expected the be largest in this critical area. This flux is used to determine the number of lanes required. Then we follow the convergence lines from the far end. As soon as the flux exceeds the capacity of the lanes placed there, we add one more lane. At the wall, it is obvious that new lanes will be added to the interior of the area. In the example, the wall hugging lane for the area where people move to the right will has receives its share at about the 45^{th} cell to the right. From there on a second lane is defined, from which entering the first lane is no longer possible. This will be filled at about the 56^{th} cell to the right, and so on until 5 lanes are defined.

At the inner convergence line, the situation is a little more complicated. Simply adding lanes to the side where people come from is not correct. These lanes would interfere with the lanes near the wall. In Fig. 3 we see that most people will reach the critical area following the inner convergence line, the flux along the wall does not require an additional line. What is needed is a change in the floor field in a block of cells such that the inner convergence line is moved away from the end of the wall and a gap a few cells wide is opened for the required number of lanes, see Fig. 4. Similarly, the floor field is changed in front of the exit and at the right end of the space within the inner walls, such that the convergence lines do not extend from the walls but from points a few cells away. With this, the cutting of corners will be reduced and the space actually used allows a passing with fairly high density, but without a jam.

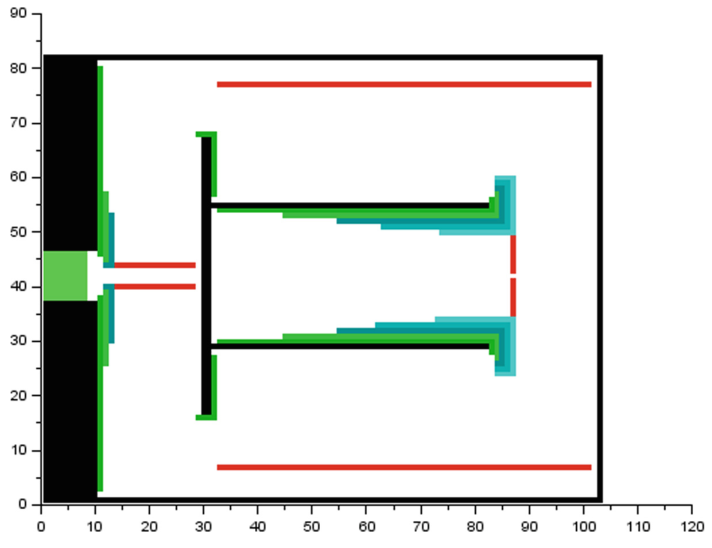

Fig. 4. Lanes (green/blue) and shifted inner convergence line (red) (Color figure online)

In many cases, it is not necessary to construct the lanes in the floor field, an opening two or three cells width will automatically be utilized quite well, because of the sideways movement if forward movement is blocked. For good performance on wider gaps, lanes at the new inner convergence line must be formed in the same way as near the walls. In the area concerned, the CA simulation is not fully realistic in all cases, the unisotropy of the grid gives unrealistic preferred individual pathways.

The lanes will end in a line leading out from the last cell of the convergence line. Test showed that small variations in the length of the lanes have no effect on performance, just on local pathways. What has to be avoided is a situation where the flux from the outer lane end tends inward as will happen with outer lanes that are too short.

Within the lanes, we redefine the floor field. The high probability step will be forward within the lane, and changing lanes will get a medium probability to get a local equilibration of usage. With these measures, the CA performance around corners will be fairly realistic.

3.3 Results

The procedure has been tested for a number of geometries, the one of Fig. 2 being the most complicated one. In all cases the results were satisfactory, while standard CA simulations showed unrealistic behaviors (jams) at all corners where our procedure estimated a need for more than two lanes. For the modified floor field, we can see that the number of cells heavily used at the corner is sufficient to give the required flow and the full width of the exit is utilized (Fig. 6). This is a big improvement over the standard floor field, where only two cells each are heavily used at the upper and lower corners of the wall and at the corners of the exit, with one more cell in moderate use. For the modified floor field, there are high densities near the corner, but they do not act as effective bottlenecks. The only effective bottleneck is the exit, which is used to capacity for almost the entire simulation time. What is not realistic is the shape of the plume of persons in the jam, they would in reality be accumulation more in front of the exit and not near the wall. This improvement also results in a much faster evacuation - 505 versus 764 time steps.

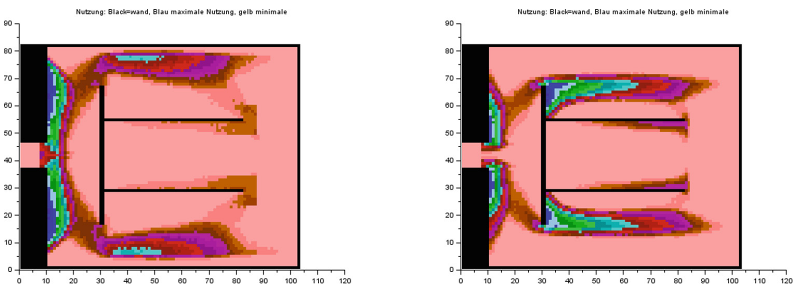

Fig. 5. Utilisation of tiles, colors and dimensions as above. left: modified floorfield, right: standard

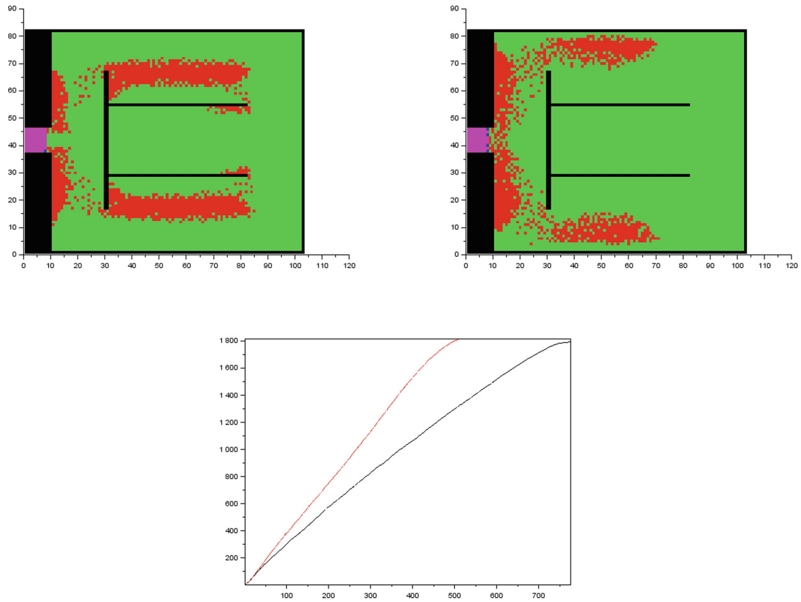

Fig. 6. Left: Positions at time step 200 for the standard floor field. right: for the modified floor field. bottom: People exited against time steps, black - standard, red - modified. (Color figure online)

3.4 Treating Variations in Time

The determination may either be done once for the entire simulation or repeatedly for a shorter period. In the latter case, the starting configuration for the predictive simulation should be taken from the final time step of the actual simulation, and the predictive simulation will run only for a limited time. The modified floor field will then be valid only for that time. This is useful if there are strong variations in the situation over time. The additional computing time needed for the predictive simulation is about the same for both cases, chopping the run into parts will not much change the required time. However, the time needed for setting up the new floor field will approximately be multiplied with the number of prediction runs. This can possibly be reduced by using incremental changes, but the present work does not include any tests in this direction (Fig. 5).

4 Conclusion and Outlook

CA methods still are very far from getting realistic individual trajectories or realistic distributions of people waiting in a jam, but with the proposed treatment of corners they can give realistic flows and evacuation times even for quite complicated buildings or sites. As long as large scale jams are avoided, the accuracy is sufficient to give e.g. a crowd manager an idea about what could be an upcoming situation. The speed of the simulation is high, available equipment will do for a faster than real time simulation. Constructing a floor field adaptively from monitoring the situation near the critical points can help, especially with the density distribution. A remaining problem of CA methods is the unisotropy introduced. This can be reduced by using hexagonal cells or Moore neighbourhood. The guidance near corners should be possible for these approaches, too, but has not yet been tried. Both approaches will be a topic of further research.

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