CELLULAR AUTOMATA MODELING OF PEDESTRIAN MOVEMENTS

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Abstract

An approach is taken to modeling pedestrian movements which attempts to capture the behaviors of pedestrians at the micro level while attaining realistic macro level activity. This approach is based on a Cellular Automata (CA) rule set that emulates actual pedestrian goals such as minimizing distance traveled and avoidance of conflicts with others. The emergent group behavior is an outgrowth of the interaction of the rule set in simulation.

The approach taken is for pedestrians in a large open space such as a rail or bus terminal, shopping mall, or office lobby where conflicting movements at high volumes would tend to cause congestion and reduce overall flows of persons. A particular rule set is examined for emergent group behavior which is examined as a hypothetical model for actual pedestrian flow patterns in crowds. The approach is also applicable to pedestrians on sidewalks, at street corners, and in traffic crossing lanes. The modeling effort to date has enhanced the investigation of what behaviors to look for in determining the important rules for pedestrian decisions and movements.

Introduction

This paper presents an application of CA to pedestrian movements in crowded spaces. CA is an artificial life approach to simulation modeling and is named after the principle of *automata* (entities) occupying *cells* according to localized neighborhood rules of occupancy [1]. The CA local rules emulate the behavior of automata, in this case pedestrians. This CA model applies the rule set of the automata (pedestrians) to a lattice of cells, such as a pedestrian walkway or lobby.

Pedestrian movements exhibit flexible and unrestricted dynamic path choices. Pedestrian flows are not restricted to channelized lanes and can intermix in conflicting flows, making them substantially different from vehicle flows which generally conflict at intersections. The turbulence of pedestrian movements is largely intractable using mathematical methods. As discrete entities that move with short-term step choices, pedestrian movements are a logical candidate for CA modeling, and to the authors' knowledge have not been previously treated.

CA car-following models have demonstrated advantages in capturing, through local rule sets, the emergent macroscopic behavior as appropriate speed-flow-density relationships [2]. The CA automobile models exhibit non-linear speed transitions and self-organized criticality that is present in actual shock waves [3, 4]. Most promising for CA traffic modeling is that high-density chaotic traffic phenomena are difficult to capture with equation-based models and that the short-term inter-vehicular reactions of drivers can be approximated by a limited rule set.

The lack of microscopic pedestrian models speaks to the complexity of the task of modeling the conflicting and flexible movements. In drawing from the example of car-following CA, it is encouraging that the emergent aggregate behavior is realistic. The pedestrian rule set is necessarily more complex and intuitively based, since pedestrian path choice and inter-pedestrian actions at the micro level are less constrained than auto movements, dynamic, and not well defined. The goal of this CA modeling effort is to

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determine the essential factors that inform pedestrian decision making and to create a rule set that results in realistic emergent group behavior.

The "Grand Central Station Problem"

Pedestrians are discrete entities that progress in steps and follow flexible, yet logical rules, ideal conditions for a CA metaphor of behavior. The most common situation for pedestrians is the special case of 2-way corridor or sidewalk movements. Conflicts can be minimized by keeping to the right, but its modeling can be non-trivial because of unbalanced flows and the many problems that can arise, such as a disruption in flow from cross traffic, stoppages, and so on. The problem of analyzing multidirectional microscopic behavior in a crowded open space is more general and intractable without simulation modeling. The case of an open space where pedestrian movements arise from 4 directions is more difficult to analyze and important enough in large facility design to attract interest. This generalized pedestrian movement problem is termed in this paper the "Grand Central Station Problem" (GCSP) after the crowded rush hour conditions that regularly arise even in that immense space.

Local Rule Set

To examine this GCSP, a hypothetical floor area or matrix of cells (i, j) is selected into which a number N persons enter in each time step T_i and proceed to the opposite side. In the general problem a pedestrian may enter by any of the four sides. The origin (i_o, j_o) and destination (i_d, j_d) cells are selected from random distributions. A pedestrian entity finds its way from an origin cell to a destination cell by following local behavioral rules. It is generally true that pedestrians avoid collisions or conflicts of path choice. In less crowded spaces this is not difficult, but as the pedestrian density increases, it becomes necessary to maneuver around occupied cells. When maneuvering is blocked, if the pedestrian stays put, such CA rules will result in a jam up where pedestrians are locked into position. This unrealistic situation is avoided by adding an ability to sidestep into an adjacent cell, forcing the occupant to sidestep as well. Though not envisioned as a physical bump, but rather as an assertive movement, it is referred to in this paper as a "bump" for the sake of brevity.

In Figure 1 the sides of a matrix of cells are numbered 1 through 4 clockwise from the top. In the first time step shown, entity 11 enters the matrix from Side 1 in cell (0, 1). The destination on Side 3 is through cell (3, 2) which is highlighted for illustration. In the second time step in Figure 1 entity 12 enters from Side 3 through cell (3, 1), also highlighted. Its destination is through cell (0, 3). The desired movements based on the local rules for entities 11 and 12 are shown with arrows.

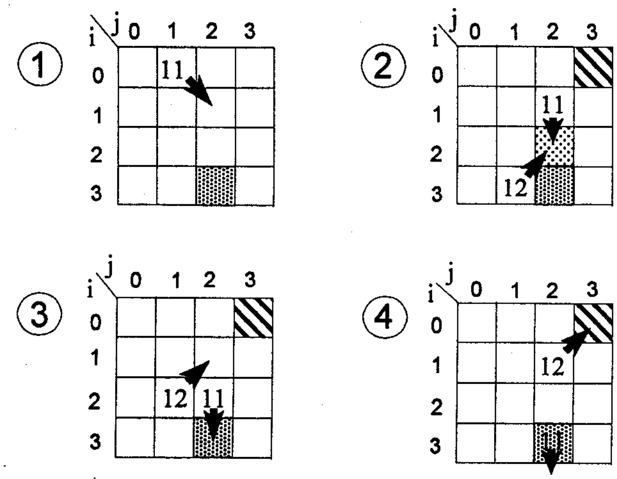

Figure 1: Illustration of pedestrian movements in four consecutive time steps.

Several possibilities for pedestrian maneuvers around blockages are posited in this paper. These include adjustments, sidesteps, and bumps. These maneuvers around blocked cells and the complete local rule set for pedestrians follows.

Pedestrian Local Rules: In each time step T_i every entity in entity number sequence moves one step. The pedestrian attempts to move forward, adjusting the path if necessary; if forward movement is blocked, the pedestrian sidesteps; if the desired sidestep cell is occupied, the pedestrian moves into that cell, "bumping" the occupant into a sidestep relative to its forward movement. If its sidestep cell is occupied, it bumps, and so on, until an entity finds an empty cell or is bumped off the floor matrix. When bumped, an entity does not lose its turn to move forward. The local rules for a new entity entering from Side 1 are explained in more detail next.

An entity enters the matrix at time T_i at an origin cell (i_o, j_o) and assigned an entity number e_n until it reaches the opposite side at its destination cell (i_d, j_d).

In the next time step T_{i+1} , entity e_n selects a cell in the next cell layer toward (i_d, j_d). If $j_d - j_o = 0$, the entity chooses to move to the cell directly ahead $(i_o + 1, j_o)$. If that cell is occupied by another entity, the entity "adjusts" its path by choosing with equal probability either diagonal cell ahead $(i_o + 1, j_o \pm 1)$ without going off the matrix. If the three forward cells are occupied or off the matrix, the entity tries to sidestep.

For the sidestep when $j_d - j_o = 0$, the entity chooses with equal probability either cell to the side $(i_o, j_o \pm 1)$ without going off the matrix. If that cell is occupied, the entity bumps the occupant.

If $j_d - j_o \neq 0$, the entity chooses to move to the cell diagonal cell ahead and toward its destination cell $(i_o + 1, j_o \pm 1)$. If this cell is occupied, it adjusts its path by choosing the cell directly ahead $(i_o + 1, j_o)$. If that cell is occupied, the entity tries to sidestep.

For the sidestep when $j_d - j_o \neq 0$, it chooses the cell to the side closest to the destination $(i_o, j_o \pm 1)$ without going off the matrix. If that cell is occupied, the entity bumps the occupant.

In bumping, the bumper leaves its space and occupies the desired cell to the side. The bumped entity moves to the side closest to the destination or arbitrarily to either side if $j_d - j_o = 0$. This entity bumps the occupant if the desired cell is occupied. A bumped entity may leave the matrix if it is bumped off it. Bumping is recursive and may result in several bumps before an entity finds an empty cell or leaves the matrix.

The local rule set is illustrated in Figure 1. In time step 2 entity 11 moves diagonally from its origin cell toward its destination cell as entity 12 is created in cell (3, 1). Both desire to occupy cell (2, 2) (see dotted cell). Since entity 11 will move first, it takes cell (2, 2), while entity 12 adjusts its cell choice to cell (2, 1). The entities proceed on after time step 3 without interruption. This simple illustration of path adjustment for entity 12, is similarly extended to sidestepping and bumping as described above.

Simulation Experiments

This CA model can be run with pedestrians entering the floor matrix randomly from four sides. For simplicity the case of constant arrival rates is exclusively studied, though dynamic arrival rates exhibiting peaking of demand from a particular direction (e.g., departures from a train) is a distinct possibility for future study. In this paper the most general case examined is for a constant arrival rate of four pedestrians in each time step randomly originating from any of four sides of a 15 x 15 cell matrix. The number of maneuver steps is a measure of turbulence.

The model was run for 3000 time steps. If pedestrians walk at 4 fps (2.7 mph), then for cells of 2 foot x 2 foot each time step represents 0.5 seconds (2 cells/sec) and 3000 time steps take 25 minutes. As a steady state condition, this does not represent a long period of time but is sufficient to reveal some basic indications of performance and turbulence.

Figure 2 shows the frequency of the number of steps taken by each pedestrian. The minimum number of steps to cross the floor is 15. When pedestrians encounter traffic, they maneuver through the traffic with adjustment steps, sidesteps, and bumps that may cause the number of total steps to increase. The mean number of steps taken is 16.9.

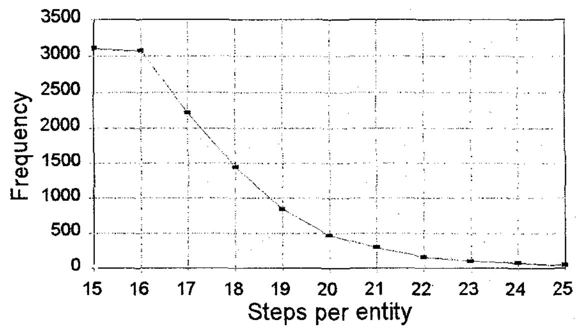

Figure 2: Frequency of all steps.

This general case of constant arrivals from four sides exhibits maneuvers around conflicts that are quite involved. Figure 3 shows the Frequency of Adjustments, Sidesteps, and Bumps for each pedestrian. The distributions reveal patterns that would not necessarily have been expected. Very few entities at this volume of flow make no adjustments and most commonly make three. Sidesteps and bumps are increasingly less frequent, as would be expected. Most commonly, an entity makes a total of four maneuvers in its emergent path. Some entities make 15–20 extra steps in their path with many of these steps from adjustment steps. Adjustment steps do not slow the entity, but are simple course corrections that reflect the turbulence in flow. Sidesteps and especially

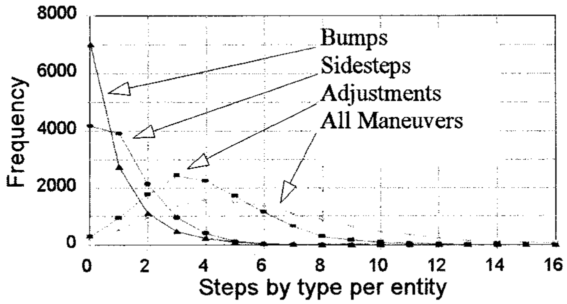

Figure 3: Frequency of maneuver steps.

bumps are exhibitions of turbulence. Not often are there five or more sidesteps or bumps for an entity. The maneuver distributions are Poisson in nature, a distribution that often reflects the nature of the occurrence of chance events. The presence of such a distribution, if found in actual pedestrian maneuvering behavior, would help to validate the local rules.

Figure 4 illustrates the magnitude of floor occupancy changes in each time step. In each time step four pedestrians enter the floor lattice. Generally, four will also leave, making the net gain usually zero. Since four always enter, for there to be a net loss of four entities, eight must exit in a time step. This results when there is significant maneuvering. The normal curve is indicative of emergent behavior that also would not necessarily have been expected.

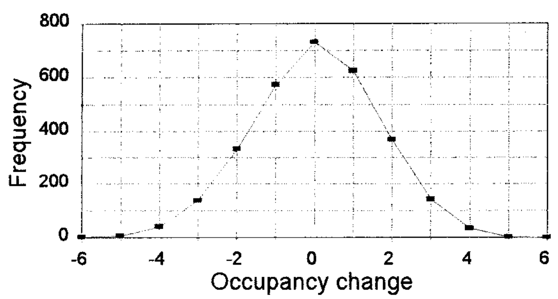

Figure 4: Frequency of floor occupancy change in a time step.

Conclusions

Though the rule set used is rudimentary and preliminary to more realistic treatment, it is instructive that this CA model is capable of processing many of the possible movements of pedestrians in crowds. It is left to further study to determine what would be closer to a more complete rule set for pedestrian CA microsimulation. The model presented here is the best known rule set to date. As universal simulators, CA models appear capable of representing any pedestrian behaviors that are deemed appropriate.

The process of creating a CA model of pedestrian movements provokes in depth thought of the behavior of pedestrians and how to model their probable actions. The CA format allows for treatment of otherwise intractable actions and can be taken considerably further.

As mentioned earlier, dynamic arrival rates exhibiting peaking of demand from a particular direction (as when passengers depart from a train) are a distinct possibility for future study. Blockages to flow such as an information booth, luggage, and so on can be placed on the floor and pedestrian flows studied. Pedestrians often travel in pairs and small groups that operate with a cohesive rule set when encountering traffic blockages. Intelligence can be added to the pedestrians so that they have more foresight in their next cell choice. Speeds could vary from person to person and with conditions. Pedestrian types could be treated as random variables in simulation. Video of crowded places like Grand Central Station will be studied for path maneuvering behavior exhibited by pedestrians.

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