Emergent Crowd Behavior from the Microsimulation of Individual Pedestrians

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Abstract

Modeling pedestrian traffic at the micro-level is a relatively young research area. The key to success is driven on the ability to appropriately model crowd behavior that arises in pedestrian traffic. One method of validation for such simulation models examines their ability to reproduce commonly observed crowd behavior. This paper demonstrates how commonly observed crowd behavior emerges from the few simple navigation rules the Intermodal Simulator for the Analysis of Pedestrian Traffic (ISAPT) system employs for each individual pedestrian.

Keywords
Pedestrian micro-simulation, pedestrian navigation behavior, pedestrian traffic.

1. Introduction

The ability to model pedestrian behavior provides a foundation for the development of a variety of tools that can be used by designers to evaluate the impact of building design on the level of service provided to pedestrian traffic. An important aspect of modeling pedestrian traffic is the ability to appropriately model the crowd dynamics that arise naturally. Examples of observed crowd behavior reported in the literature include lane formation, formation of stripes at intersections, velocity variations based on position, etc. Different approaches have been used to model crowd behavior with micro-simulation being one of the most recent methodologies. The idea is to rely on the micro-level simulation of the interactions between the individual pedestrians to generate appropriate macro-level behavior of the crowd.

Capturing realistic pedestrian behavior in simulation is useful for evaluation and planning in building design [1, 2], urban design [3], land use [4], marketing [5], and traffic operations [6]. The goal of our research is to develop a system that can be used as an aid for designers and planners in the evaluation and operation of intermodal facilities. In order for such a system to become a reality, a means is needed to develop the logic needed to simulate human navigation behavior, particularly in crowds. In reactive navigation a pedestrian navigates based on its reaction to items within the environment. Such methods include the use of social force fields [7], rule based methods [8], and XZT space methods [9]. Even though these methods permit a pedestrian to navigate, the pedestrian still requires some overall goal or direction that motivates it to move. Therefore, it is not uncommon to see these reactive methods used in combination with a defined target that a pedestrian is trying to reach, or a path that it is following. This paper will discuss the methods ISAPT (an Intermodal Simulator for the Analysis of Pedestrian Traffic) uses to simulate the micro-level navigational behavior of individual pedestrians via a rule-based approach. Based on this simulated behavior, the paper will demonstrate the emergent crowd behavior produced from the simulation.

2. Behavior Simulation

The ISAPT system is an OpenGL-based application written in the C++ programming language with an aim at supporting cross-platform use. The simulation was developed using the OpenSteer toolkit [10] that provides a foundation for the development of an individual behavior-based simulation making use of an existing graphical architecture. A pedestrian is represented in the simulation as a point mass with the capability for linear momentum. A pedestrian is defined in terms of their position, mass, velocity, direction, and limitations (i.e., maximum force and speed). Since we are simulating humans, a pedestrian’s velocity arises from forces that are self-generated and modified by changes in these forces (referred to as steering forces). The simulation employs a fixed time advance mechanism with the movement of each pedestrian within the simulation being dictated by a steering force vector.
that is the compilation of a set of individual steering forces derived from individual behaviors programmed into the system. This steering force vector is resolved into a position and velocity for the pedestrian. Unlike the 2D grid-based approaches commonly employed, the ISAPT system utilizes a three-dimensional (3D) spatially continuous domain to describe the position and movement of a pedestrian. Each pedestrian’s position is defined in terms of a 3D point in space, and vectors are employed to represent their velocity and acceleration all defined with respect to some point in time within the simulation. The Euler equations are used to simulate the physics of realistic movement of a pedestrian. Using these equations, the movement of every pedestrian in the simulation is updated in response to a change in their steering force vector prior to incrementing the simulation clock. The basic behaviors, currently employed within ISAPT, that contribute to the overall steering force include moving forward (in a specified direction), path following, target seeking, braking, as well as collision detection and avoidance of both stationary (i.e., benches) and moving obstacles (i.e., pedestrians). These individual behaviors represent the basic building blocks ISAPT uses as a means for simulating more complex macro level behavior (e.g., formation of lanes in pedestrian traffic). The logic used in determining how best to combine the steering force contribution of each of these behaviors to determine the overall steering force vector applied by the pedestrian is shown in Figure 1.

The basic drive of a pedestrian within the ISAPT system is to move along a path from its origin to its destination. A pedestrian’s current speed will be the same as their desired speed and remain constant unless an impending collision is detected. If a collision is detected with one or more other pedestrians or obstacles then the pedestrian or object they will collide with first is labeled as the principle threat and an appropriate steering response or speed change is sought. The logic used for making this determination is shown in Figure 2.

In ISAPT, the collision detection mechanism explores the immediate vicinity of each pedestrian looking for obstacles or other pedestrians that represent potential future threats. The system extrapolates the future paths of the pedestrians in the vicinity exploring successive time periods out in the future. Then a collision is tagged between pedestrians when the distance between them is less than the sum of their radii plus a set personal space attribute of each pedestrian. A collision with a stationary obstacle is identified if any part of the pedestrian intersects with the obstacle’s boundary.

The angle between the direction of the pedestrian and its threat is used to determine which of three cases to employ in determining an appropriate steering response (except in the case of obstacles which all fall under the head-on case since an obstacle has direction). For the case of a head-on collision, the area in front of the pedestrian (its field of view, FOV) is bisected and a density measure is calculated for each side taking into account all pedestrians within a defined immediate area (e.g., 3 meter...
distance in FOV). The density measure takes into account the distance and relative direction of each pedestrian in each half of the FOV. The equation is:

$$\text{Density Measure} = \sum_i \left( \frac{\text{direction}_i}{\text{distance}_i} \right)$$

(1)

Pedestrians moving in the same direction are favored over those moving in the opposite direction. The further away a pedestrian is the less impact it has on the measure. Following consideration of all other pedestrians in the area, the pedestrian’s avoidance maneuver will be to the side with the smaller density measure. The density considerations of individual pedestrians are what contribute to lane formation in pedestrian traffic.

In the second case, when it has been determined that the pedestrian is going to run into the back side of the threat, the system will make either a speed or direction change. The decision to change speed as opposed to direction is handled using probabilistic settings with speed changes occurring $x\%$ of the time and direction changes $(1-x)\%$ of the time with $x > (1-x)$. A value of 80% is used for $x$ in the current implementation, but as with this and other probabilistic values used in the logic, future studies are needed to determine an appropriate value for this setting. The speed adjustment is prescribed using the equation:

$$s(t) = s(t-1) \times \left( \frac{t_1}{t_2} \right)$$

(2)

Where $t_1$ is the time until the pedestrian will collide with their closest threat, $t_2$ is the lead time period into the future within which potential collisions are considered. Given that $t_1 < t_2$, a speed reduction will result in each iteration as long as a detection is detected. This logic results in a controlled slowing in successive iterations as the pedestrian approaches the threat. Eventually, the other pedestrian will no longer represent a threat. In the situations, for the second case, where a direction change is made, the system will again compute left and right-hand side density measures (as in the head-on case) and steer in the direction with a lower density value.

The last of the three cases involves those situations where a pedestrian will collide with the side of the threat, where its side is defined as a range covering approximately 45 degrees from the front and extends 110 degrees to its backside. If the pedestrian will collide within that span past the 90 degree mark (back side), then a response of change direction or reducing speed is employed in the same manner as for the second case discussed above. If the collision is determined to be on the front-side of the threat then the pedestrian will speed up to avoid the collision using the inverse of the equation (2) above.

In all case where a direction change is made, either in response to a stationary or moving object, the pedestrian will return to a trajectory in the direction of their original path given the logic of Figure 1. This return is guided by the contribution of two steering behaviors, one that seeks to move along the path and the other that contributes to seeking the target destination. Each of these can be weighted to impact their contribution.

3. Macro Level Behavior

The contents of this section demonstrate the macro level behavior capabilities of ISAPT that arise from the simulated micro-level behavior of the individual pedestrians. Some of these behaviors may seem obvious, but one must keep in mind that these behaviors are not directly programmed, but emerge from pedestrian interactions that result from the logic, presented in Section 2, that governs the micro-level navigation of each individual pedestrian.

3.1 Speed as a Function of Density

Given the many reports on the fact that pedestrian walking speed is most significantly impacted by traffic density, we desired to see if the micro-simulation of pedestrian traffic would reproduce this behavior. ISAPT was set up to simulate unidirectional traffic moving down a hallway that is 8 meters wide. The region of interest for observation was a 26 meter length of the hallway containing no other entry or exit points. The pedestrians were initially distributed throughout the hallway in both the horizontal and vertical direction. The desired velocity of each pedestrian was generated from a normal distribution with a mean of 1.2 m/sec and a standard deviation of 0.2 m/sec.

When a pedestrian exits the region of interest, the system would reintroduce that pedestrian back at the start of the hallway with their initial position across the width of the hallway (y-value) at the entry point being determined using equation (3) where the current position is altered by a normally distributed value (mean zero and variance of 1) whose value is constrained to +/- 0.5 meters.

$$\text{New Y-Position} = \text{Current Y-Position} + \text{Clip( N(0,1), -0.5, 0.5)}$$

(3)
Using this approach, the number of pedestrians was kept constant in each simulation run and ranged from 20 to 220 pedestrians. Given that the desired speed (free flow) of each pedestrian varied, the cycle time of each pedestrian was logged after an initial warm-up period. The average cycle time of each pedestrian was then computed and expressed as a fraction of their free-flow speed.

The results of these runs are shown in Figure 4 where the average fraction of free flow speed for all pedestrians is plotted versus the available area per pedestrian in the system. These results illustrate that ISAPT correctly simulated the trend whereby pedestrian traffic slows as traffic density increases. An early published report by Fruin [11] illustrating the impact traffic density has on speed for pedestrian in a walkway is shown in the same figure for comparison. The graph represents the results fitting a curve to the observations reported by Fruin. Note the similarity in the shape of the curves with the greatest difference being 10% at high density (1 m²/s).

### 3.2 Lane Formation in Bidirectional Flow

When pedestrian density exceeds a critical value, dynamic lanes emerge. The pedestrian lanes consist of pedestrians that share the same intended direction and approximately the same velocity. When two lanes are formed, the division generally occurs in the center of the walkway. Using the same hallway setup as was simulated above, experiments were run to determine if the micro-level simulation of pedestrian behavior would result in the formation of lanes. The previous setup was modified such that the number of pedestrians would be equally divided between those going in each of the two directions in the hallway. The initial conditions were such that the pedestrians were randomly placed on their side of the hallway resulting in an initial mass chaos of pedestrian movement as they strive to navigate to the opposite end. Figure 5 illustrates the initial conditions for a run with 80 total pedestrians in the system.

<table>
<thead>
<tr>
<th>Number of Pedestrians</th>
<th>No. Lanes</th>
<th>Lane: Flow Direction / Width (m) / Occupancy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Top Lane Middle Lane Bottom Lane</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>Right / 2 / 12 Left / 4.5 / 20 Right / 1.5 / 8</td>
</tr>
<tr>
<td>60</td>
<td>3</td>
<td>Right / 2.5 / 21 Left / 4.5 / 30 Right / 1 / 9</td>
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<td>3</td>
<td>Right / 2 / 17 Left / 4 / 40 Right / 2 / 23</td>
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<td>Left / 2 / 26 Right / 4 / 50 Left / 2 / 24</td>
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</tr>
<tr>
<td>140</td>
<td>3</td>
<td>Right / 2 / 33 Left / 4 / 70 Right / 2 / 37</td>
</tr>
<tr>
<td>200</td>
<td>2</td>
<td>Right / 4 / 100 Left / 4 / 100</td>
</tr>
</tbody>
</table>

Figure 6. Lane formation for 80 pedestrians.
Multiple simulation runs were made with different numbers of pedestrians in the system to illustrate the various lane formation behaviors that would result. Table 1 shows the results from running ISAPT for various crowd densities. This table reports on the direction of each lane, its average width, and the number of pedestrians occupying the lane. Three lanes form in most cases, but the number of lanes and the direction of the lanes vary. Figure 6 illustrates the case where two lane form as a result of the interaction of the 80 pedestrians within the system. Lane formation occurs quite quickly with the initial semblance of lanes appearing within 30 seconds and clear lane distinctions with almost no deviation at around 70 to 100 seconds into the run.

Pedestrians prefer to walk behind another pedestrian rather than make their own path. By joining an existing travel lane, a pedestrian is able to minimize interactions that require avoidance maneuvers. This leads to more efficient travel for pedestrians [12][13]. Figure 7 illustrates this phenomenon for the case involving 120 pedestrians in their formation of three lanes.

### 3.3 Speed Distribution across a Hallway
Pedestrians who have a faster speed than the average lane travel tend towards the outer edges of the walkways. This was tested using the same hallway setup for the case of 80 pedestrians moving in two lanes of bidirectional flow (same as shown in Figure 5). Speed data of each pedestrian was collected as they passed through a 0.1 m wide vertical zone halfway down the hallway. This zone was further subdivided into 0.2 m blocks and the speed and position of each pedestrian whose center passed through this block was averaged. Graphs of these results are shown in Figure 8 and illustrate a speed gradient supporting observed behavior.

### 3.4 Stripping Formation in Pedestrian Cross Flow
The emergent behavior at walkway intersections depends on the number of walking directions present. When only two traffic directions are present at an intersection, striping formations emerge. If the two directions are exactly opposite, the striping becomes lane formation. If, however, the two directions are not exactly opposite, pedestrians form stripes to proceed through the intersection. This is most noticeable when two wide streams of pedestrians intersect [13]. The emergence of stripes allows pedestrians to move through the intersection without the need to stop. Similar to lane formation, striping at intersections maximizes travel efficiency by limiting obstructions and increasing average speed. To test this behavior, an intersection between two hallways was modeled in ISAPT with the method of pedestrian generation being identical to that used in previous experiments. As illustrated in Figure 9, the simulated pedestrians exhibit this behavior.

### 4. Conclusions
To accurately model pedestrian behavior, ISAPT utilizes microsimulation, populating the simulation...
with agents capable of direction and speed changes. The individual agents make these changes based on their use of a simple set of navigation rules. The validity of these micro-behaviors has been demonstrated through emergent macro-behaviors. The crowd level behaviors are not programmed into the simulation. Rather, they emerge as a result of the individual actions of each agent. The formation of lanes, speed/density relationship, speed distribution, and striping at intersections all verify the accuracy of the pedestrian behavior.

The ISAPT system is currently being modified to make use of discrete choice models for both navigation and wayfinding. Additional human studies are being conducted to quantify pedestrian speed and trajectory changes, zones of comfort, and crowd behavior patterns.

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**References**