Behavioral Intelligence for Geospatial Agents in Urban Environments

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Abstract

Existing models of virtual humans in urban settings have largely focused on algorithmic or graphical efficiency. They look *realistic but are relatively lacking as experimental tools. In this paper, we introduce a novel approach to modeling urban crowds, based on individual and collective geospatial intelligence.*

1. Introduction

Traditional geospatial models of urban pedestrians have focused on gravity-based spatial interaction, statistical relationships, queuing, and discrete choice. These models are useful for coarse representations of flow but limited in treating micro-scale dynamics and complex adaptive attributes [1, 2]. Newer models in computer science have advanced capability following work in populating virtual worlds with believable avatars, level-of-detail rendering and algorithmic design for path-planning [3, 4]. Design of non-player characters in video games as also contributed, as has modeling in kinesiology and gait and motion capture, although this is not urban-specific. Work in physics using models based on random walks and Brownian motion, gas and fluid particle streams, and force-fields has added further innovation [5]. Similarly, research in urban design has advanced understanding of viewsheds and the influence of streetscapes on movement [6]. Avenues for research inquiry remain, however. Existing models in computer science are often designed to look plausible, but not necessarily behave realistically. They are often AI-based, relating to algorithmic efficiency rather than treating the full range of human behavior. Physics work focuses largely on very high density crowds, where analogies to physical flows can be made. This abstracts from the full and rich behavior of human activity. Urban design work emphasizes infrastructure in human-environment interaction, rather than behavior.

In this paper, we introduce a model based on geosimulation methodology (which is described more fully in [7]), which offers distinct advantages over conventional approaches. First, the traditional consideration of average and spatially-modifiable geographical units or (statistically) mean individuals is replaced in geosimulation. Instead, units are regarded as spatially non-modifiable entities, with individual descriptions and independent functionality. Where aggregates are considered, they are formulated generatively, built from the bottom up by assembling individual entities for the purposes of accomplishing an aggregate task or amassing an aggregate structure. Second, simulated entities are independent and autonomous in their behavior. The independence is significant; attention in model-building turns to the specification of individual-level behaviors. Also, entity behavior is not necessarily treated as homogenous across the system being considered or static over the lifetime of a phenomenon. Third, models are commonly designed as event-driven, rather than time-driven, where events are cast as discrete packets of change, based on the independent internal clocks of simulated components. When put together to form a system, update of these clocks may be flexibly-defined and the methodology can reconcile diverse temporal scales.

Cellular automata (CA) are widely deployed in geosimulation of pedestrian and crowd behavior, but remain limited in their ability to best represent the systems that they are used to model. The principal limitation is a disjoint between CA methodologies and our knowledge of spatial dynamics. In particular, CA must use diffusion as a proxy for real movement. They also rely on fixed, symmetric neighborhood filters to govern spatial interaction. Depending on the temporal update scheme used to govern state transitions, CA often have difficulties in reconciling the space-time dynamics of mobile entity positioning because of a reliance on state-exchange as a substitute for movement vectors. Agent automata are much more suitable for pedestrian simulation, but have not been traditionally built with much geospatial functionality, likely because they have been pioneered in fields outside the geographical sciences and despite the potential benefits of infusing agent-based approaches with geospatial functionality.

A novel approach to agent-based geosimulation of activity in urban environments is introduced in this paper. Geographic Automata Systems (GAS) are

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employed as a computational vehicle for simulating large dynamic behavioral collectives of independent urban agents [8]. The use of GAS has the advantage of endowing simulated entities with geospatial intelligence atop standard agent-based functionality common to models of this kind: an ontology of automata entities with varied spatial abilities; flexible treatment of the space in which modeled entities exist; diverse mechanisms for spatial and temporal interaction; and manifold processes to govern the geospatial and geotemporal locations of modeled entities in a spatial environment. GAS also carry a natural affinity with Geographic Information Systems and Geographic Information Science, with the added benefit of interoperability between simulations and such systems for calibration and validation.

The result is a framework of agents that are capable of acting and interacting with each other and the built environment with synthetic geospatial intelligence, and a seamless connection to spatial analysis as a mechanism for calibrating and validating applied simulations. The usefulness of the approach is demonstrated through application to mass evacuation scenarios.

2. The underlying behavioral model

Several conceptual ideas and hypotheses underpin the basic formulation of our model, drawn from behavioral geography, psychology, urban geography, decision theory, urban design and planning, and sociology.

We treat individual actors as the atomic units of behavioral dynamics. Agent-actors are built as independent, autonomous Geographic Automata (G); crowds are formed as GAS collectives. G are given individual states (S) and rules (R_S) to govern their transition as the simulation unfolds. G may be located by any geo-referencing convention (L) and can also move through the spaces they occupy by any locomotion regime (R_L). L allow G to be registered in space and time (i.e. $L = L_t$), either directly or indirectly, on a one-to-one, one-to-many, many-to-one, or many-to-many basis. A typology or ontology (K) of G entities mediates the nature of L and R_L. Input to G is considered *geographically* as neighborhoods of interaction and influence. G neighborhoods may differ heterogeneously in extent and shape per G and may change dynamically so that $N = N_t$. Neighborhood rules (R_N) determine these changes. Neighborhood relationships, expressed as cognitive filters, social relationships, lines-of-sight, and so on can be introduced and allowed to vary over space and time. Many G may be combined in a systems context, with each G in the collective GAS coded heterogeneously.

$$G \sim (K, S, R_S, L, R_L, N, R_N), \text{ where } R_S: S_t \rightarrow S_{t+1}; \; R_L: L_t \rightarrow L_{t+1}; \text{ and } R_N: N_t \rightarrow N_{t+1} \quad \text{(i)}$$

Five *entity types* are simulated: World, FixedObjects, MobileObjects, Goals, and Probes. World represents the simulated city. It encapsulates all other entities in the simulation and provides georeferencing, handling entities' absolute position in the World and their position relative to other entities in the World. FixedObjects represents the urban infrastructure and thus handles buildings and obstacles (parked cars, trees). FixedObjects do not move, although they can influence the movement of other mobile entities. MobileObjects represent people in isolation, crowds and the groups that they form, as well as particles (smoke, embers, mobile toxins). MobileObjects move, as the nomenclature suggests. Goals are used to structure events as beacons/anchors for actions to be executed. Goals may be used by specific groups or individuals, in specific places and/or at specific times. Probes capture attributes of the simulation (as an executable computer program), the simulated system (as a synthetic representation of phenomena of interest or under study), and model entities' states and actions. Probes are endowed with the ability to sift through data, sort it, and exchange it with caches for input/output to/from Geographic Information Systems (GIS) and statistical analysis.

Pedestrian agents are heterogeneously endowed with characteristics from a synthetic data population, using statistical, geostatistical, and geodemographic inference to down-scale aggregate data sources. Motion capture and motion editing are used to produce realistic-looking movement, heterogeneously, per-agent. The technique also provides upper- and lower-bounds for pedestrian velocity, as well as free speed.

Use of geosimulation and GAS allows for novel ensembles of entities to form collectives by accident and through collaboration or conflict. We make use of social network analysis to capture the emergence of such ensembles in simulation. This is done quantitatively: groups are identified, stored, and analyzed as graph-network structures in GIS.

There is space-time choreography to human movement and activity. We know, for example, that use of space for travel is subject to constraints that anchor people in space and time (they have to be at work by 9 a.m. and would like to be at home by 5:30 p.m., for example). Walkers may organize their paths through space-time as events fashioned around their activity goals and these anchors. We have developed an integrated analytical spatiotemporal toolkit for capturing the time geography of agents, allowing for space-time paths and prisms to be determined for agents or groups. Space-time paths allow us to build a map of activities in space *and* time. Space-time prisms help to illustrate the space of possibilities for a space-time path, e.g., given certain space-time anchors, what is the potential range of behavior for an event, person, or group?

People use waypoints to develop a general sense of how to get somewhere. To accommodate this, path planning is introduced to the modeling framework per-agent as a search heuristic, whereby agents plan their route between waypoints before mobilizing. This path, encoded as a graph, represents their cognitive map of city. The algorithm calculates the cost to get from a start node to another node (g); an estimate of travel cost from a node to the goal (h); and an estimate of the total cost of traveling from start to finish through a given node (f). Low values of f are consistent with short paths. (Below, x is the path at a given stage in the search.)

$$f(x) = g(x) \times h(x) \qquad \text{(ii)}$$

Calculation of h can be flexibly performed in GIS and swapped into/out of simulations, allowing for frictional effects (α) on travel, such that we consider distance-decay ($h^{-\alpha}$), for example.

People use spatial cognition to detect and avoid collisions. When free from crowds, people maximize their personal space buffer. When they do encounter traffic, pedestrian scanning for collisions takes place in a small ellipse, ignoring features at a distance. This scanning area changes size/shape based on speed and ambient density. Moreover, pedestrians pick-up on and interpret subtle signals in body language as part of their scanning behavior. Pedestrians are very effective at adjusting their space-time movement to avoid contact with other pedestrians or obstacles. They avoid borders with monotonically declining distance-decay. They will also preemptively correct steering and velocity to avoid a collision. This may involve near-impact step-and-slide movements. Regularities are often present in such behavior. Pedestrians are known to favor the right-hand-side in avoidance maneuvering, across cultures. They also tend to yield wide berth to groups.

We use a combination of these approaches in representing agents' spatial cognition. Walkers project an individual-centric geography around themselves, used to filter the world as they move, formed as a vision cone centered on the agent and cast (around a ray) in a forward direction. Cones have heterogeneous form with lengths and arcs varying based on changes in pedestrians' behavior, characteristics, and surroundings. Potential collisions are registered in an array and sorted for relevance (angry dogs may get priority for some people, but not others, for example) as the cone comes into contact with entities and as other entities enter into the cone. The first relevant entry that counts as a noteworthy collision prompts the agent to take corrective action to avoid an encounter. Collision spheres are mapped to *G*'s skeletal rig in simulation and collision-checking is performed for each sphere when contact occurs within *G*'s cognitive filter. This allows pedestrians to react to each others' body language (encoded using motion capture data).

3. Applying the model: The dynamics of mass evacuation in dense urban settings

We have tested the usefulness of the modeling scheme through application to a scenario of mass evacuation from a dense urban area. 300 agents are synthetically-derived with life-like attribute and instructed to evacuate a downtown area by foot. Individual behavior among the agents soon yields to crowd dynamics as agents encounter mass congestion (Figure 1). Jams form dynamically in the collective, due to urban design and because of individual compression and expansion in space-time trajectories (Figure 2). Jam events propagate backwards against the predominant tide of crowd flow, much as highway traffic jams form. By fusing the simulation with GIS, we are able to track individual and collective motions, actions, and interactions and subject them to spatial and social network analyses. Space-time paths and agents' social networks are shown in Figures 2 and 3.

4. Conclusions

We have proven the usefulness of adopting geospatial intelligence to drive behavior in models of urban dynamics through application to evacuation dynamics in downtown settings. The scheme demonstrates the potential for approaches of this kind in exploring and generating theory in studying spatial cognition, sociality, collective behavior, and human-environment interaction.

5. Acknowledgements

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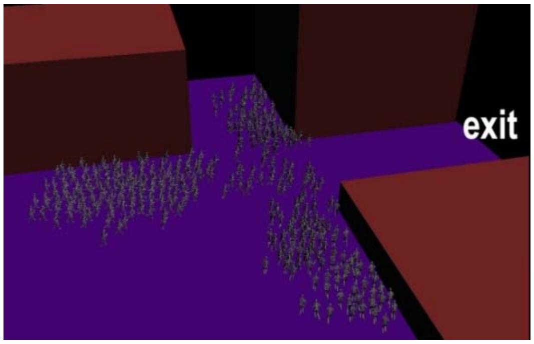
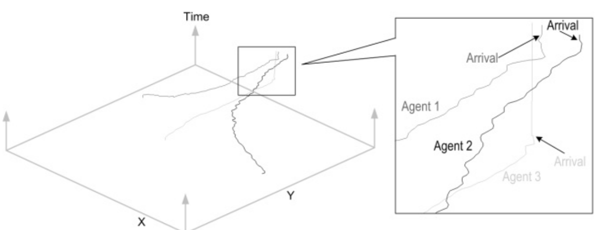


(a)

(b)

Figure 2. (a) Pedestrians flee to an exit. (b) The crowd and environment cause congestion to lock-in (shown in with full texture-mapping and rendering).



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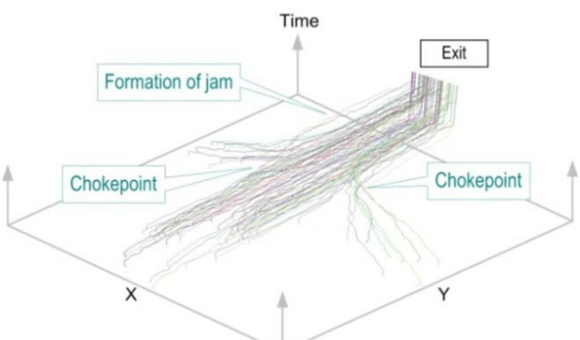

(b)

Figure 3. Select (a) and all (b) space-time paths. Spatiotemporal expansion/compression waves are evident in individual space-time trajectories (a), and jams and chokepoints show in the collective profile (b).

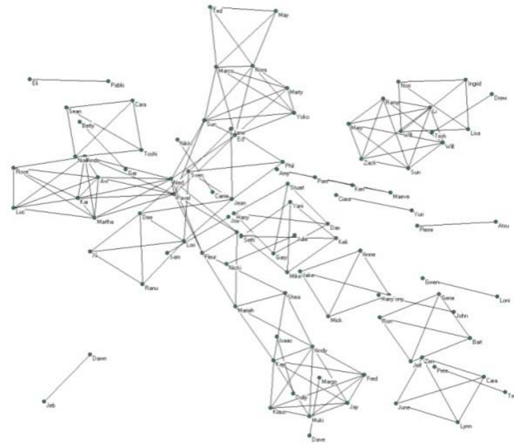

Figure 3. Social networks of family/friend ties among agents at $t = 10s$ in the simulation.

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