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A realistic outdoor urban pedestrian mobility model

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ABSTRACT

Existing generative mobility models, used to produce mobility data for simulated agents in, e.g., wireless network simulations, suffer from a number of limitations. Most significantly, existing models are not representative of actual human movement. We introduce a new mobility model based on state-of-the-art work in understanding pedestrian mobility patterns in urban areas, known as Space Syntax. Under our model, agents move in a meaningful fashion in terms of destination selection and pathfinding, constrained by their surroundings in an outdoor urban environment. Our model is implemented as the publicly available Destination-Based Space Syntax Simulator (DBS3). We use DBS3 to demonstrate which mobility model parameters affect wireless network simulations: centrality bias significantly affects network simulation results in non-grid-based urban centres, whereas the pathfinding metric affects results more in grid-based urban centres; distance decay has minimal impact on our wireless network metrics.

1. Introduction

Simulation studies of wireless network protocols require a source of mobility data for the agents in each experiment. Trace data obtained from tracking actual movement of real people is an appropriate source of such mobility data. However, it is impractical to collect accurate mobility traces for a large number of people, each individually tracked over a lengthy period of time. Using an electronic device like a cellular phone or laptop as a proxy for each person, for example, yields trace data of limited granularity, with successive locations inferred from associations with access points or cellular towers. Additionally, the collection of trace data is limited to those times when the device is both active and can communicate with the fixed infrastructure.

However, the most pressing issue when resorting to mobility traces is that traces collected in one environment do not generalize to different spatial configurations,[1] i.e., to a different building, campus, or city layout. In sharp contrast, generality is a strength of generative mobility models. A generative mobility model is an algorithm that, using an entropy source (e.g., a pseudorandom number generator), produces simulated movement for each agent in an environment. The random waypoint mobility model [1] is one such generative model. Agents moving according to this model proceed in straight lines to randomly chosen destinations in a featureless environment, pausing at each destination for a random amount of time before choosing a new destination and speed. The random waypoint model is an instance of the more general random trip model [2], in which agents moving in a bounded, connected domain move to random destinations according to predetermined destination-selection and mobility rules. Numerous mobility models similar to random waypoint exist, and they have been surveyed extensively [3].

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[1] We use the terms "configured" and "configuration" to mean any environment where not every point is accessible by a human, i.e., an environment with rigid obstacles to free movement.

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It is well understood that random waypoint and models directly derived from it are not ideal mobility models to use in a simulation. There are mathematical concerns with these models, such as average agent speed continuously decaying over time in the absence of a positive lower bound on random agent speeds [4]. But the largest problem with random waypoint is a fundamental one: it is not a realistic representation of human movement. People do not move in unobstructed lines to random locations in a featureless environment. This problem is more than aesthetic, since the choice of mobility model can significantly affect the results of a network simulation [3]. Despite these issues, the random waypoint mobility model continues to be used [5,6].

The key problem that this paper addresses is *how to combine the generalizability of a generative mobility model with the ability to honour both the restrictions and meaningful patterns of human mobility in configured spaces*. Needless to say, we want this combination to be practically useful in simulation studies. As the most important objective of a simulation study is a comparison of a number of systems under a representative range of inputs, we would like to minimize the population of cases constituting a defensible "representation." Therefore, an important—if somewhat informal—constraint is to limit reasonably the degrees of freedom in the parameter space. Our goal is thus to strike a workable balance between the desire to capture the essential patterns of human mobility and the ease of description of a modelled case.

One critical observation is that it does not suffice simply to move agents between random points on an outdoor street map by routes that minimize Euclidean distance travelled. Human movement is not characterized by such simple rules. Our problem thus becomes *finding a theory that describes human mobility adequately and that can be used to derive an easily and naturally parameterizable algorithmic, generative mobility model*. This paper adopts the view on how configured space influences human mobility as it is articulated in the theory of Space Syntax [7]. Space Syntax is now a relatively mature theory, focused on the design of urban (built) environments. Potential lines of movement unobstructed by rigid obstacles, called *axial lines*, collectively define the *axial map* of an area. Space Syntax seeks to understand how people perceive distance, move, and cluster on any axial map. The key result from Space Syntax is that the most heavily frequented locations in an urban environment are those that are better "integrated"—that is, locations that are a short distance away from many other locations. This observation allows us to approach the construction of the mobility model by relying strictly on the graph-theoretic properties of the map that the agents populate, without the need for additional metadata such as the locations and characteristics of popular shops or other attractions. While those attributes are not irrelevant for the accuracy of description, their inclusion would significantly complicate the model by introducing lots of fuzzy parameters, thereby greatly reducing the model's practical appeal. It is in fact one of the most interesting features of our approach that all those "popularity" parameters of the various spots on the map are implicitly captured by their purely graph-like connectedness with other spots. This is because highly frequented attractions cannot be located in poorly connected areas—the natural feedback cycle of urban development takes care of the requisite correlation. A second key result from Space Syntax is that humans do not perceive the distance between two locations as the Euclidean distance that must be travelled between them. Rather, we perceive distance as the number of changes in direction of travel, or the magnitude of change in direction of travel, that we must make to move between the two destinations.

Based on these two key results, we built the Destination-Based Space Syntax Simulator (DBS3). DBS3 1.1.1 is a freely available,[2] high-performance mobility simulator for agents in outdoor urban environments. We begin in Section 2 by describing how DBS3 is distinct from related work on realistic mobility models. Section 3 describes the design of our new mobility model. It also describes the implementation details of DBS3, in particular the new multi-expansion A* search (MEA*) used to produce optimal non-Euclidean-distance pathfinding. Section 4 then verifies the correctness of the mobility model by showing high correlation between the mobility patterns produced in DBS3 and observed pedestrian patterns in downtown Edmonton. Finally, we conclude and discuss future work in Section 5.

2. Related work

There are two main existing methodologies for building realistic mobility models. The first methodology is to extrapolate a generative mobility model from traces of actual human movement. Yoon et al. [8] capture coarse-grained trace data using Wi-Fi connectivity logs on a campus. This coarse-grained data is subsequently broken into trips between ordered pairs (i.e., origins and destinations) of enumerated locations on a campus map. The *n*-minimal set of paths (measured by Euclidean distance) between origin and destination pairs form the set of possible routes used by their generative model. That approach is subsequently extended [9] to consider the time of day, adding realism by considering when students on campus are more likely to travel between different locations. In fact, the mobility patterns of a fixed individual have a high level of predictibility given the current time of day [10].

The second existing methodology used to build realistic mobility models is to survey individuals to learn how they move in a given environment. Hsu et al. [11] manually defined locations of interest on a campus, then generated a Markovian transition model between these locations by conducting a survey of students. A more involved approach was used by Feeley et al. [12]. They developed a system that not only defined locations of interests, but also sets of activities to be performed by agents at those locations. What activities each agent would perform is determined by the role of that agent, which is drawn from a manually defined set. A similar but time-dependent approach [13] constructed a generative model using surveys of

[2] Available on-request; please contact the authors by email.