Knowledge-Based Approach to Modeling Urban Dynamics

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Abstract. The model representing the complexity of the pedestrian mobility has to incorporate the nature of the modeled phenomenon by accounting the interdependence between human behavior and urban environment. Our efforts are directed towards correlating emergent behavior patterns of different types of pedestrians to contextual knowledge that will help us map realistic pedestrian behavior into agent's decision making capabilities. We propose that agent's beliefs, goals and decision-making strategies should be derived directly from the integrated urban knowledge. Causal probabilistic models that are based on Bayesian inference are proposed as a potential solution to some of the challenges in the pedestrian agent modeling.

Keywords: Pedestrian modeling · Bayesian inference · Multi-agent simulation

1 Introduction

Urban systems are complex systems, very difficult to delimitate, evolving through space and time. If the general structures of urban systems are complex, the behaviors that can be observed are far from being entirely stochastic [2]. Our knowledge of urban phenomena might have been deepened on many levels, though its modeling and computational representation is still an open problem [6]. The idea of a city as an urban space that is sustained by human connections requires suitable models that recognize the sound interplay between physical and phenomenological aspects of the urban system. Our approach to urban modeling resembles the anthropological view [14]; a network perspective of a city as an interconnection of people, urban elements and their dynamic relationships and processes. This alternative perspective places humans and their experience, rather than urban form, at the center stage of the metropolis view.

Agent-based models possess suitable capabilities required for modeling structural and behavioral properties of real-world urban systems, since the complex agencies are directly modeled and the behavioral properties of the agencies can be explicitly specified in terms of meaningful operations and applicable knowledge rules. Multi-agent models provide facilities for simulating the entities, processes and interactions involved in urban dynamics, making them applicable to a wide range of urban problems, and suitable for dealing with both the macro-level (societal) and the micro-level (individuals) aspects of urban systems.

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There is a very natural way to simulate various moving entities in a city (e.g. pedestrians, transportation) within multi-agent models. Models of pedestrian mobility vary in the level of detail, abstraction and design approach [11–13]. Trajectory patterns can be considered as spatiotemporal evidence of movement behavior i.e., the footprints of the confrontation between the physical urban system and individuals' behavior that give rise to the structure of the city. In [11], data mining techniques play a fundamental role for extracting patterns from trajectory data gathered by means of location-based and sensing technologies. Pedestrian behavior at the microscopic level (e.g. pedestrian speed, inter-pedestrian positions) and its implications to agent modeling is presented in [12]. Suitability of an extensive set of algorithms for representation of real-world pedestrian trajectory data is discussed in [13].

Our long-term goal has been to layout a foundation for developing a multi-agent system that will accommodate our future exploration of different research scenarios related to pedestrian mobility. Our interest is in the manifestations generated by interconnecting elements at a higher level of aggregation and abstraction, rather than the behavior of individuals at a microscopic level. Our efforts are directed towards correlating emergent behavior patterns of different types of pedestrians to contextual knowledge that will help us map realistic pedestrian behavior into agent's decision making capabilities. The premise was that the more that is known about the factors affecting behavior, trends and processes before we start modeling, the better design choices for agent modeling could be expected.

2 Urban Knowledge

Creation of a knowledge base that pertains to urban modeling is of crucial importance for creating more effective urban environment models, both for holistic views of a city or specialized scenarios of a particular urban area. There is an urgent need for converging knowledge representation that requires unity of models, strategies and perspectives, contributed by the relevant disciplines and experts (Fig. 1). The knowledge base should provide a means for integrating and interconnecting traditional urban knowledge data such as urban maps, photographs, cadaster data, and various unstructured data (A), as

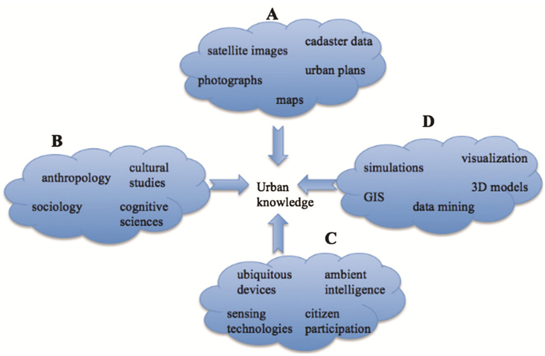

Fig. 1. Integrated urban knowledge base

well as empirical studies and social surveys (B). This effort needs access to heterogeneous data, solicited and gathered by experts in various fields (e.g. architects, city planners, social science experts) with various solicitation and analytical methods. Semantic heterogeneity, terminology differences, inconsistency, redundant data and interoperability are some of the problems that might be encountered.

The new directions in information technologies aimed at pervasiveness and intelligence have increased the amount of raw data collection with a potential to increase our knowledge of different aspects of social urban life. The employment of a number of tools and intelligent techniques could support the process of capturing and visualizing the observable manifestation of behavior trends and patterns i.e. the urban dynamics (C). Correlating observable and emergent patterns of behavior with other urban-related knowledge that can help us make sense of the underlying complex systems is an imperative (D). Extracting qualitative knowledge from large quantities of data is just the beginning of the search for meaning and plausible explanation of urban dynamics.

Validation is critical when modeling complex dynamic systems, hence integrated urban knowledge have been recognized to serve both purposes, interpretation and understanding of the studied behavior, and as a captured and measured historical and empirical manifestations against which model outcomes could be evaluated.

Our long-term goal has been to layout a foundation for developing a multi-agent system that will accommodate our future exploration of different research scenarios related to pedestrian mobility. The first phase in designing agents that will represent real-life pedestrians was to create an appropriate urban context representation as a basis for modeling pedestrian mobility.

We have examined the ways in which human movement decisions might be influenced by various demographic, situational and environmental factors that characterize the context in which pedestrians move.

Table 1. Urban knowledge categories related to pedestrian movement.

Type of knowledge	Knowledge category
Environmental factors	• Street type (characteristics) • Destination/attractors • Integration value • Visual fields • Level of services • Level of comfort • Popularity
Situational factors	• Traffic intensity • Season • Time of day • Seasonal/daily events
Individual/group factors	• Stereotypical type • Preferences • Demographics • Visit frequency

A variety of urban context data (situational and environmental) and additional pragmatic factors were identified and investigated to have a prominent role in establishing appropriate urban knowledge for our particular research (Table 1). Some of these categories represent invariant properties of the urban context that can be obtained from domain-specific urban knowledge, and the specifics of the particular scenario. Others should be drawn from the information gathered from a variety of sources (e.g., social studies, ambient and smart technologies). The set of selected categories could be broken down into three groups: (1) environmental factors, (2) situational factors reflecting the particularities of a given situation, and (3) characteristics to account for the individual and group perspectives. The justification for the selection of the characteristics is based on the theory and empirical evidence reported in relevant literature.

Pedestrian agents will be situated in a particular urban environment, which may have a profound effect on their decision-making strategies and behavior. A number of environmental factors that describe the local urban context should be explored in order to establish their impact on pedestrian movement. The environmental factors capture the physicality and the dynamics of the urban space where the human mobility takes place. Steady progress has been made toward identifying and understanding what factors may have an impact on pedestrian movement trough a certain urban space. Street morphology [2, 12], level of integration value [10], spatial configuration [2], visual fields [4], level of service and comfort [7], etc. have been pointed out to affect human movement in different urban context scenarios. Identifying the attractors and possible destinations is a way to reason about pedestrians' goals and plans.

The inclusion of situational factors attributes substantially greater sensitivity in agents' behavior, namely, the ability to adapt to temporal constraints, or the particularity of a given situation (2). Recognizing situations associated with daily events, random gatherings, excessive traffic and crowd-related behavior are crucial since they are more likely to affect pedestrian behavior. Temporal aspects of pedestrian dynamics should be accounted for, which may sometimes constrain the goal-oriented behavior of pedestrians, other times may generate new incentives, goals and plans.

Individual and group categories are included to support the representation and reasoning about a particular situation as a pedestrian views it (3). These categories lie somewhere on a specialization scale from generic to individual. Generic categories target stereotypical pedestrian groups (e.g., preferences, emergent behavior), as opposed to individual user characteristics specific to a single user. Demographic characteristics such as: age, gender, etc., should be accounted for if their effect is known to manifest in the domain under investigation. The behavior of pedestrians who are frequent visitors of an area may exhibit different patterns from pedestrians, who visit it rarely or for the first time.

3 Agent-Based Modelling of Pedestrian Dynamics

Agents can only perform as well as their representations of the task they are trying to perform and of the world they are trying to perform in [15]. We can gather evidence and capture the footprints of human behavior, though the explanation and interpretation used for modeling purposes must be interdisciplinary, theoretically and empirically plausible contributions. We propose that agent's beliefs, goals and decision-making strategies should be derived directly from the integrated urban knowledge. Movement decisions correlated to goals, surroundings, and situational circumstances have to be appropriately accounted for. Our modeling efforts are directed toward gathering evidence of the pedestrian behavior. An agent model that is derived from realistic pedestrian behavior is expected to represent pedestrian complex interactions with the physicality and particularity of the urban space.

Pedestrian behavior can be described at three major levels: strategic, tactical, and operational level [7]. Human actions and behavior are purposeful and meaningful; people do not move in urban spaces for inexplicable reasons, they move because of the activity they are engaged in. This goal-directed behavior of pedestrians is represented at the strategic level. The tactical level is an expression of short-term decisions regarding pedestrian movement within a particular urban area (e.g. sequence, route, temporal constraints). At the operational level, a pedestrian makes swift decisions as a response to immediate environmental and situational circumstances (e.g. daily events, traffic intensity). Models of pedestrian mobility may vary in the level of detail for the pedestrian strategic, tactical or operational behavior to suit the research purposes.

Individual pieces of urban knowledge or a collection of categories do not constitute a model. The efforts to find out how those pieces of information are related to each other and affect pedestrian mobility are far more challenging. How can all of this information be combined to support agent's reasoning capabilities that closely approximate realistic pedestrian patterns? We argue that causal probabilistic models that are based on Bayesian inference provide a potential solution to some of the challenges in the pedestrian agent reasoning. It provides a formal method for quantifying uncertainty by combining diverse types of evidence including both subjective beliefs (expert and participants) and objective data. Explanations of behavior derived from realistic causal model are more likely to match the reality, because the model accounts for deeper and richer relationships underneath data and simplistic statistical analysis.

Bayesian Belief Networks (BBNs) are suitable for representing the causal relationship between different pieces of information, as well as the rules for how to use, maintain, and reason with urban-related knowledge. The Bayesian network representing agent's reasoning and decisions regarding pedestrian movement is shown in Fig. 2. It should be noted the figure depicts variables and relations only on the highest level; in practice the network could be quite complex. As shown, the agent movement decisions are related to the states of three hypothetical (non-observable) variables: Strategic Movement Decisions, Tactical Movement Decisions, and Operational Movement Decisions. Each of the hypothetical variables is linked to the relevant urban knowledge categories (drawn as oval boxes), which correspond to the categories discussed in previous section (Table 1). Once the knowledge categories are identified, a suitable classification would be needed to categorize them.

The decisions at higher abstraction levels (strategic) seemed to only partially describe a particular movement behavior. Examination of lower-level decisions was needed especially for describing short-term decisions (tactical level) and random situations. Hence, the goal-oriented view (strategic level) would be contrasted with inherent

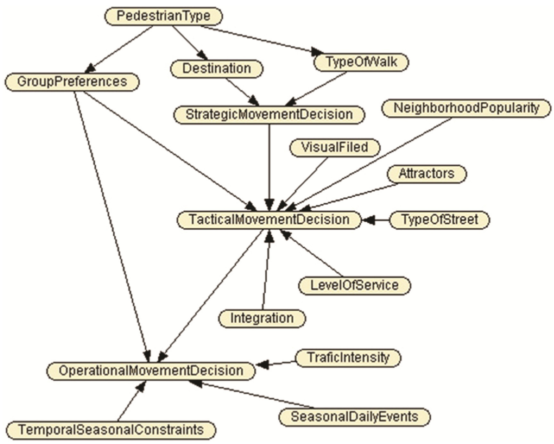

Fig. 2. High-level dependencies between urban knowledge categories for pedestrian agent reasoning

attitudes, preferences and randomness in human and crowd behavior. The strategic movement decisions are expected to generate the space of possible routes to a chosen destination, while tactical movement decisions would simulate a path selection at each intersection. Human randomness, group fuzziness and crowd behavior are necessary for more realistic modeling of pedestrian movement in an uncertain environment and will be derived as a final decision, i.e. operational movement decision.

To apply the proposed framework for modeling pedestrian mobility in a particular urban domain requires: (1) a selection of the knowledge categories relevant in that particular domain; (2) an identification of the sources of information and intelligent techniques needed for establishing the states of variables; and (3) a construction and training of the Bayesian network which includes the relationships amongst the urban categories and the specification of the conditional probabilities implied by the relationships.

4 Case Study

Skopje's Old Bazaar, a mediaeval city fragment with a unique appearance was the focus in our case study, a sample solution that may, by analogy, suggest ways to tackle problems that might be encountered in another context. The Old Bazaar historically has always been a center of commerce, which determined the structure of its urban space and the distribution of its buildings and visitors. Consequently, the area of the Old Bazaar has been and still is mainly constituted of places of trade, commerce and services, with few cultural and historical sites that serve as attractors for tourists.

Agents modeling have started by identifying different agent types to represent distinct entities and processes at play in the enclosed urban area. Several aggregated agent types were selected to represent different pedestrians at strategic level, namely, tourists, transit pedestrians, employees and visitors of various service providers (public, private). One should note that visitors to religious facilities and people in search for nightlife entertainment represent different stereotypical groups that entail different modeling strategies. Space-syntax models were deemed more suitable for modeling tourist agent behavior, while utility-based approach was employed for modeling other agent types.

A number of realistic trajectories were collected from the history of pedestrian activity [10], which were used to establish the space of possible routes associated with aggregated pedestrian types. The visualization of the recorded pedestrian data has revealed several patterns with specific spatial and time distribution. It provided insights into both movement patterns and overall system behavior. The selection and categorization of the taxonomic factors was followed by the phase of constructing the BBN-based model to serve as agent knowledge representation. The urban context factors were interrelated and built into agents reasoning mechanism. The Bayesian network was constructed and trained off-line with the pilot study data as a training set. The training set was used to adjust the corresponding causal probabilities of the BBN nodes. Agent design went through iterative refinements, empirically consistent with the existing knowledge (surveys, historical data, statistics, observations).

A number of environmental factors that described the local context in terms of urban structure were explored in order to establish their impact and sensitivity during pedestrian route-finding decisions (tactical behavior). The overall integration value of the street network in the Old Bazaar indicates that highly-integrated streets are the ones in the middle of the area, while the peripheral streets have lower integration values [10]. The exhibited pattern coincides well with the most frequented pedestrian routes. Data analysis has confirmed pedestrian preference for streets that are visually open and connected to the other parts of the route. The observed preference of wider non-deserted, though not overly crowded streets, has been considered [10].

The identification of attractors governing pedestrian dynamics within our context of interest was one of the objectives for gathering exhaustive context knowledge. Each urban entity or area, private and commercial, identified as a possible attractor or destination, were enriched by several context attributes such as type, functionality, ownership, working hours, demographics, number of employees, frequency of visitors, etc. The pedestrian routes and paths were described according to their accessibility, obstacles, sun exposure, street lights positions, dimensions, and throughput, in order to take into account how the characteristics of the real environment affect and constrain the pedestrian movement. Entities and areas outside the Old Bazaar perimeter were also included to account for the fact that their attraction, prominence and affordance may distinctively affect different agent type's behavior by extending the space of destinations.

We have examined how much the states of the variables linked to movement decisions influence the beliefs about that node. The results have confirmed that neighborhood attractions, the street type and the visual fields were most likely to produce the greatest change in the associated beliefs. Street features, nearby attractor buildings, and time of the day were found to have significant impact on the movement preferences across the pedestrian types.

Situational factors that characterize the particular scenario have been accounted for to simulate the exhibited behavior on an operational level. The immediate attraction to ongoing events, such as festivals, concerts, exhibitions and gatherings have been taken into account. We concluded that a number of influential factors affect the way humans negotiate the urban space, which points at their relevance for inclusion in the causal probability models for agent reasoning.

Heterogeneity in the real world, observed through anthropological surveys and empirical studies, provided valuable insights for distinguishing relevant aggregated agent types as well as for rules governing their goal-directed behavior. The results of all participants were aggregated to distinguish behavior and patterns based on a particular scenario and context, rather than of individual participants, so that aggregated agents can make independent decisions within previously established behavioral guidelines.

We have used knowledge discovery to help us in identifying and interpreting patterns relevant to our agent modeling. A number of data mining exploration studies to discover the associative and causal relationships between factors have been conducted and are still in progress. Discovering meaningful relationships between urban knowledge categories and the emerging collective behavior has been a crucial step in increasing the quality of the current agent design and future validations. Our aim was to improve our understanding of how stereotypical pedestrians behave, and how their movement was guided (affected) by the various situational and environmental factors expected to influence their interaction with this particular urban area.

Samples of movement behavior of three agents presented in Fig. 3 represent the following situation: (a) a tourist pedestrian agent on a way to a historical site visits a random lines of authentic filigree jewelry shops, (b) a transit pedestrian agent on its way to a selected destination randomly stops at a nearby shop, and (c) a transit pedestrian agent who takes the originally established shortest route to a selected destination point. The popularity of attractors is based on empirical studies results (e.g., traffic/visit frequency, surveys).

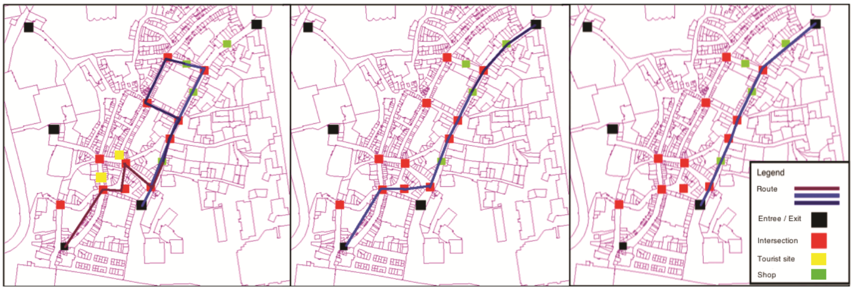

Fig. 3. Simulated agent behavior. (a) A tourist pedestrian agent visiting several places of interest. (b) A transit pedestrian agent visiting a random shop. (c) A transit pedestrian agent taking the shortest route to destination without any stops (https://www.youtube.com/watch?v=2un0eyFHpq0). (Color figure online)

Each time a specified situation arises (e.g., intersection, event, nearby attraction), the agent deliberates and makes a decision, either by generating a new route or staying on the same course of movement. If a new goal is established, network beliefs will be recalculated and updated. If the goal remains unchanged, the originally established route will be followed, or the original route could slightly deviate to accommodate a random choice (e.g., lunch time, local happening). Color coding (different route colors) is used to represent the points of deliberation and new decisions.

During simulation, a number of agents of different types simultaneously move through the area. The distribution of agents for each agent type reflects the real-life statistics and frequencies, their behavior is autonomous and different, but within previously established behavioral guidelines. For example, we may have agents of a certain type, one who selects less crowded path, while the other chooses to mix with the crowds (out of curiosity). The presence of multiple pedestrian agents on the scene would result in strengthening or weakening of the level of attraction of a certain entity, and even generate new attractions on the run.

5 Conclusions

This paper has presented a knowledge-based approach to modeling pedestrian mobility in urban spaces. Bayesian belief networks were proposed to provide a suitable representation of the causal relationship between different pieces of urban information and to integrate rules for agent's reasoning and decision making. The knowledge space is expected to provide a starting point with enough possibilities to account for the complexity and the relationship among urban dynamics of different nature and with the same depth as it was explored in our case studies. Experimentation with multi-agent models are expected to lead the way to a better understanding of the general processes and conditions at play in the urban world.

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