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Data-driven spatio-temporal discretization for pedestrian flow characterization

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ABSTRACT

We propose a novel approach to pedestrian flow characterization. The definitions of density, flow and velocity existing in the literature are extended through a data-driven spatio-temporal discretization framework. The framework is based on three-dimensional Voronoi diagrams. Synthetic data is used to empirically investigate the performance of the approach and to illustrate its advantages. Our approach outperforms the considered approaches from the literature in terms of the robustness with respect to the simulation noise and with respect to the sampling frequency. Additionally, the proposed approach is by design (i) independent from an arbitrarily chosen discretization; (ii) appropriate for the multidirectional composition of pedestrian traffic; (iii) able to reflect the heterogeneity of the pedestrian population; and (iv) applicable to pedestrian trajectories described either analytically or as a sample of points.

1. Introduction

Research on pedestrian traffic has received growing attention during the last decades due to its importance in many aspects: planning of walking facilities under regular and safety-critical circumstances, operations in large events, description of congestion, etc. All these aspects require a sophisticated understanding and modeling of the data behind complex pedestrian movement patterns (Bierlaire and Robin, 2009). Data collection for pedestrian flow and behavior analysis used to be particularly cumbersome. Typically, manual counting methods (on-site or on videos) and surveys distributed to randomly selected individuals were the main sources of data. Nowadays, automatic pedestrian detection and tracking methods have evolved tremendously, allowing for more comprehensive analyses (Bauer et al., 2009; Alahi et al., 2014a,b; Seer et al., 2014).

To increase insights into pedestrian movements, different empirical studies were conducted and reported in the literature (Lam et al., 1995; Hoogendoorn and Daamen, 2004; Helbing et al., 2005; Schadschneider et al., 2009). For instance, it was observed that directness, habits, pleasantness, safety, pollution and noise levels are some of the important attributes for pedestrian route choice (Bovy and Stern, 2012). Other empirical studies have revealed the existence of relationships between traffic indicators (Weidmann, 1993). Self-organized structures in pedestrian flows, such as lane formation (Daamen and Hoogendoorn, 2003; Hoogendoorn and Daamen, 2004), and phenomena like stop and go waves (Helbing et al., 2007), herding (Helbing et al., 2005), the faster is slower (Helbing and Johansson, 2010), the zipper effect (Hoogendoorn and Daamen, 2005), were also empirically discovered.

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The empirical observations have inspired a number of theories and models of pedestrian movements. They are utilized to describe and predict pedestrian movement at strategic, tactical, and operational level (Hoogendoorn and Bovy, 2004). The models concerned with strategic decisions (departure time choice, activity pattern choice) are important for the assessment of pedestrian demand (Danalet et al., 2014). The models at tactical level are focused on activity scheduling and route-choice (Cheung and Lam, 1998; Stubenschrott et al., 2014). Together with the models at operational level (walking behavior), they are used to evaluate quality levels of pedestrian traffic, and have been applied to support the design and planning processes in many areas related to pedestrians (Daamen, 2004). The modeling of pedestrian walking behavior attracts a significant attention. For instance, there are approaches that are based on social force-fields (Helbing and Molnar, 1995; Zeng et al., 2014), cellular automata (Blue and Adler, 2001; Hsu and Chu, 2014), continuum flow (Hughes, 2002; Hoogendoorn et al., 2014, 2015), utility maximization (Robin et al., 2009) and queuing theory (Cheah and Smith, 1994; Løvås, 1994). A comprehensive review of the existing approaches and their evaluation can be found in Duives et al. (2013).

The fundamental variables used at both levels, to observe and to model the traffic of pedestrians, are density (k), flow (q) and velocity (v). *Density* is expressed as the number of pedestrians per unit of space at a given moment in time; *flow* is interpreted as the number of pedestrians per unit of time and per unit of length; *velocity* is expressed in meters per unit of time. Several definitions of these variables are proposed in the literature (Duives et al., 2015; Zhang, 2012). However, little concern is dedicated to the nature of spatial and temporal discretization underlying the definitions. The basic issue is that there are many possible ways to discretize continuous space and time for the purpose of defining traffic variables. Yet, studies normally report the analysis for one particular discretization scheme whose choice is often arbitrary.

Although advanced theories and pedestrian models at strategic, tactical, and operational level exit, the fundamental aspects related to pedestrian movement are still not adequately treated. The aim of this study is to utilize the potential of the data obtained using state-of-the-art tracking technologies to address this point. This becomes essential in the context of the growing data revolution and interconnected technologies that can help improve the safety and convenience of pedestrians. We propose a discretization framework that is independent from arbitrarily chosen values, and that results in a realistic and robust pedestrian flow characterization. Our approach is data-driven, and it is based on spatio-temporal Voronoi diagrams designed through the utilization of pedestrian trajectory data.

The structure of the paper is as follows. A review of related research from the literature is provided in Section 2. Section 3 provides a formal introduction of the basic elements involved in our analysis. Section 4 describes the proposed methodology for the derivation of the spatio-temporal discretization framework. Based on this framework, we derive the definitions of the pedestrian traffic variables, that is density, flow and velocity. Section 5 empirically illustrates the performance of the approach by using synthetic data. Finally, Section 6 summarizes the outcomes of the proposed methodology and determines future research directions.

2. Literature review

The issue of discretization is well recognized in geography (Openshaw, 1984; Çöltekin et al., 2011) and dynamic systems (Beck and Roepstorff, 1987). The research from the field of geography have demonstrated that the results of any spatio-temporal analysis depend severely on the underlying discretization. The problem appears in two dimensions, space and time (known as Modifiable Areal Unit Problem and Modifiable Temporal Unit Problem). For instance, analysis of data using grid-based spatial discretization differs from analysis performed using hexagon cells. Similarly, temporal discretization may distort or exaggerate the actual temporal pattern existing in data if it is based on an arbitrary choice. It is therefore essential that the discretization rely on a meaningful basis relevant for the purpose of the study. The definition of discretization scheme has to precede any attempt to define characteristics based on it.

This section first focuses on vehicular traffic characterization, that is relevant for pedestrian as well. However, for most applications in pedestrian flow theory the definitions derived in the field of vehicular traffic can not be directly used. In comparison to roadways where vehicular flow is regulated and separated by directions, the lack of strict rules for pedestrians to follow allows them to occupy any part of the walkable area and to move in a multi-directional fashion. We then present the approaches specific to pedestrian traffic characterization and their comparison.

2.1. Vehicular traffic

The most general and widely used definitions of vehicular traffic variables are proposed by Edie (1963). The definitions are derived based on the trajectories of vehicles $i = 1, \ldots, N$ in the time-space region A. The shape of the region A is usually rectangular with duration dt and length dx. The definitions are given as

$$k(A) = \frac{\sum_{i=1}^{N} t_i}{dxdt}, \qquad (1)$$

$$q(A) = \frac{\sum_{i=1}^{N} x_i}{dxdt}, \qquad (2)$$