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Characterization of multidirectional pedestrian flows based on three-dimensional Voronoi tessellations

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Abstract

Pedestrian flows that are characterized by complex interactions and congestion have become typical for many public spaces (e.g. transportation hubs, shopping malls). To provide convenience and safety for pedestrians in such infrastructures, an understanding and predicting of pedestrian flow phenomena are of the utmost importance. Speed , density and flow are three fundamental traffic variables used to observe and model pedestrian dynamics. Different definitions of these variables have been proposed in the literature (Zhang, 2012) leading to the inconsistent results, in both the measurement and modeling phase. The definitions usually rely on a discretization scheme chosen arbitrarily, in both space and time. This may generate noise in the data, and the results may be highly sensitive to minor changes of discretization. Furthermore, the definitions are commonly inspired by those from a much mature field of vehicular traffic, thus lacking the ability to capture the particularities of pedestrian flows. This especially concerns the multidirectional and heterogeneous nature of pedestrian movements, compared to the vehicular traffic which is often regulated and separated by directions. In this paper, we investigate a possibility for these issues to be addressed by adopting Edie's generalized definitions of traffic variables (Edie, 1963), through a data-driven discretization and stream-based-framework.

We propose a discretization framework designed by using three-dimensional Voronoi diagrams (Okabe et al., 2009) for the generator points sampled from pedestrian trajectories: $p_i = (x_i, y_i, t_i), i = 1, \ldots, N_p$, where N_p is the total number of points. Each point p_i represents the presence of a pedestrian at position (x_i, y_i) at time t_i. To design the discretization we define the distance between points $p_i = (x_i, y_i, t_i)$ and $p = (x, y, t)$ as:

$$d_\alpha = \sqrt{(x_i - x)^2 + (y_i - y)^2 + \alpha(t_i - t)^2}, \tag{1}$$

where α is a conversion constant expressed in meters per second, with the interpretation that 1 second in time is equivalent to α meters in space. The discretization assigns three-dimensional Voronoi cells V_i to each point p_i from available set (Figure 1) such that all points from a cell are closer to a corresponding generator than to any other, with respect to the distance d_α:

$$V_i = \{p | d_\alpha(p, p_i) \leq d_\alpha(p, p_j), \forall j\}. \tag{2}$$

The volume of a Voronoi cell V_i is denoted by $\mathrm{Vol}(V_i)$, with the unit square meters times seconds. The set of all points in V_i corresponding to a specific time t represents a set of dimension 2, or a

region in space 'belonging' to a pedestrian positioned at p_i:

$$V_i(t) = \{(x, y, t) \in V_i\}. \tag{3}$$

Similarly, the set of all points in V_i corresponding to a given location (x, y) represents a set of dimension 1, or a time interval 'occupied' by a pedestrian positioned at p_i:

$$V_i(x, y) = \{(x, y, t) \in V_i\}. \tag{4}$$

The individual temporal and spatial units obtained in this way are utilized for the specifications of speed, density and flow indicators at the disaggregated level. The proposed approach results in a set of definitions of traffic indicators that are adjusted to the reality of the flow and as much independent from the arbitrarily chosen discretization as possible.

The density of the cell V_i surrounding p_i is defined as:

$$k_i = \frac{V_i(x_i, y_i)}{Vol(V_i)}. \tag{5}$$

The unit of k_i is a number of pedestrians per square meter, as the cell $V_i(x_i, y_i)$ is a time interval.

We consider maximum distance d_i in $V_i(t_i)$ in the movement direction of a pedestrian positioned at p_i to define the flow as:

$$q_i = \frac{d_i}{Vol(V_i)}. \tag{6}$$

The unit is a number of pedestrians per meter per second.

The speed is defined as the ratio between the distance traversed and the time spent by a pedestrian in V_i:

$$v_i = \frac{d_i}{V_i(x_i, y_i)}, \tag{7}$$

with the unit meters per second. Note that upon taking the limit conditions ($t \to 0, x \to 0$ or $y \to 0$) the definitions yield the classical ones (instantaneous and local). We also consider the case when the individual trajectories are available (either in analytical form or through a very frequent tracking technology) and propose the discretization utilizing three-dimensional Voronoi diagrams for curves. In this case the definitions of the variables are provided based on three-dimensional Voronoi tubes associated to each trajectory from available set.

The proposed discretization framework is further enhanced by stream-based definitions of the variables so that they can be applied in the case of multidirectional flow composition (Nikolić and Bierlaire, 2014). Specifically, pedestrian traffic is considered being composed of different streams ($\varphi_j, j = 1, \ldots, N_s$, where N_s is the number of streams) that interact within the same space. A stream definition is direction-based and assumed to be exogenous. The exact choice of the stream configuration is left to the modeler. In this study, we show an example of a data-driven stream specification by using principal component analysis (Jolliffe, 2002). Pedestrian trajectories are assumed to contribute to the streams to some extent. The contribution is related to the angle (θ_{ij}) between the vector representing a movement direction (e_i) of a pedestrian positioned at p_i and the direction associated with the corresponding stream (φ_j). It is given by the projection of the vector e_i on the the stream φ_j as:

$$c_i^{\varphi_j} = \begin{cases} \|e_i\| \, \|\varphi_j\| \cos\theta_{ij} & : 0^\circ < \theta_{ij} \leq 90^\circ \\ 0 & : 90^\circ < \theta_{ij} \leq 180^\circ, \end{cases} \tag{8}$$

given that only specific values of the angle θ_{ij} provide meaningful measures. In this way, several directions (streams) of interest can be allocated to each point of the space along which the measurement of the fundamental indicators of pedestrian flow is possible to perform. Furthermore, the approach allows for the aggregation of indicators at the stream level for any space-time domain of interest. Note that aggregation without stream-composition may cause the indicators from the opposite directions to cancel out in specific circumstances. For instance, in a case of two equally sized groups of pedestrians walking at the same speed but in the opposite directions, the classical aggregation would lead to zero value of the resulting speed.

The consistency of the proposed definitions with the foundations of traffic flow theory is shown analytically and the advantages of the proposed approach are illustrated empirically. First, a simulated environment has been designed where density is controlled by changing the speed of pedestrians over time. Figure 1 illustrates the density maps obtained using the proposed approach for the points sampled from the trajectories of 11 pedestrians that walk from left to right: (a) with a constant speed and (b) with different speed (a group of pedestrians in the bottom-right corner is made faster). In the first case the density is constant over space and time, while in the second case the density between the two groups of pedestrians decreases over time, showing that the approach is able to reproduce the settings with uniform and non-uniform movement.

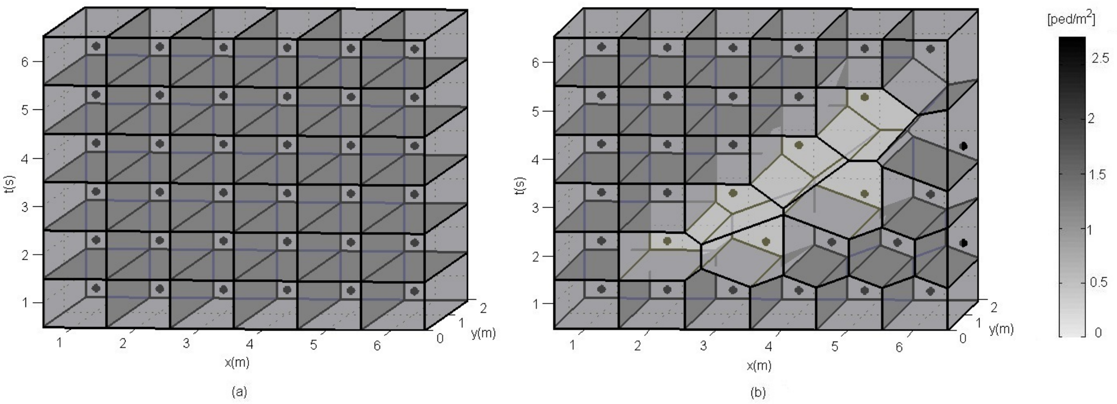

Figure 1: Three-dimensional Voronoi diagrams for a sample from pedestrian trajectories: (a) uniform and (b) non-uniform movement

The investigation performed based on individual pedestrian trajectories from the controlled experiments (Daamen and Hoogendoorn, 2003) has revealed the capability of the approach to reflect the lane formation (Figure 2) for bidirectional flows. This property makes the framework useful for the analysis of the self-organization phenomena typical for pedestrian traffic. The Voronoi cells represented by darker gray color in Figure 2 correspond to a lane formed by pedestrians from a minor stream when confronted to a major stream from the opposite direction. With the proposed approach it is also possible to correlate the momentary speed of an individual pedestrian (or a group of pedestrians) with the availability of space, and hence to analyze the effect of congestion at the microscopic level. Moreover, the approach reflects the heterogeneity of pedestrians through the detailed speed, density and flow Voronoi-based maps designed at the disaggregated level. In comparison with traditional methods (e.g. methods based on an arbitrarily selected grid discretization) based on the data from bidirectional walking experiment, the approach is shown to lead to more realistic features of measured traffic characteristics. Figure 3 shows a time sequence of density measured at specific point

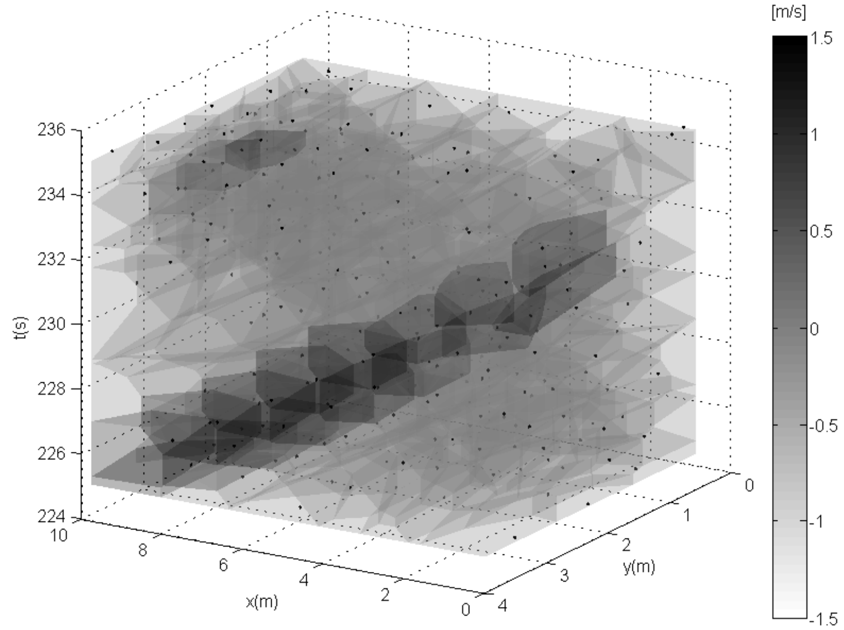

Figure 2: Self-organization phenomena revealed by three-dimensional Voronoi approach

in space using three-dimensional Voronoi (dash-dot line) and grid-based (black dots) discretization. While the latter results in large fluctuations (discontinouties), the former lead to smooth transitions in traffic characteristics.

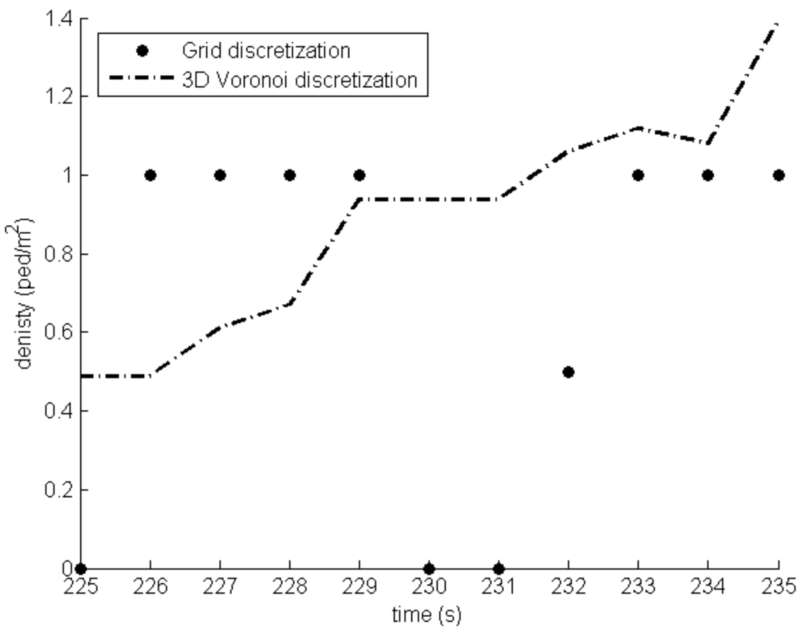

Figure 3: Time sequence of density values measured using three-dimensional Voronoi and grid based method

Additionally, the real case study (pedestrian trajectories collected in the train stations in Lausanne and Basel using technology provided by Alahi et al. (2014)) will be used to further evaluate the performance and potential shortcomings of the proposed methodology. The focus will be on the interaction of the flow indicators from conflicting streams observed predominantly during rush hours that are characterized by high level of congestion.

The presented approach provides a way of measuring pedestrian flow characteristics in a pedestrian-oriented way and by utilizing the potential of the data itself. It can also be regarded as the basis for the specification of better or improvement of existing models of pedestrian traffic. In that manner, our further research will focus on the representation of the effects of multidirectional pedestrian flows through a stream-based model of fundamental relationships.

Keywords

pedestrian flow indicators - time and space discretization - Voronoi diagram - multidirectional flows - individual trajectories

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