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Data-driven characterization of pedestrian flows

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Outline

1. Introduction
2. Methodology
   - Discretization framework
   - Definitions of the indicators
3. Empirical analysis
4. Conclusion and future work

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Pedestrian traffic

Importance

- Understanding, reproducing and forecasting phenomena that characterize pedestrian traffic is necessary in order to provide services related to pedestrian safety and convenience.

Indicators

- Density (ped/m^2), speed (m/s) and flow $(m/ped/s)$
- Used to observe and to model the flows of pedestrians
- Consistent and unified approach to the definitions of the indicators is missing

Comparison of the approaches

Properties

P_1: Consistency of the results in measurement and modeling

P_2: Compliance with multi-directional nature of pedestrian flows

P_3: Preserved heterogeneity of pedestrians

P_4: Independence of arbitrarily chosen space and time intervals over which the variables are defined

P_5: Applicability to pedestrian trajectories described analytically or as a sample of points

Method	P_1	P_2	P_3	P_4	P_5
Edie (1963)	✔	✗	✗	✗	✗
Jabari et al. (2014)	✔	✗	✔	✔	✗
van Wageningen-Kessels et al. (2014)	✔	✗	✗	✗	✗
Helbing et al. (2007)	✔	✗	✗	✗	✗
Steffen and Seyfried (2010)	✗	✔	✔	partialy	✗

Outline

Outline

Data-driven discretization framework

Pedestrian trajectories

- The trajectory of pedestrian i is a curve in space and time

$$\Gamma_i : \{p_i(t) | p_i(t) = (x_i(t), y_i(t), t)\}$$

- 3D Voronoi diagrams associated with trajectories
- Each trajectory Γ_i is associated with a 3D Voronoi 'tube' V_i

$$V_i = \{p | \min\{d_*(p, p_i) | p_i \in \Gamma_i\} \leq \min\{d_*(p, p_j) | p_j \in \Gamma_j\}, \forall j\}$$

- $d_*(p, p_i)$ - spatio-temporal assignment rule

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Data-driven discretization framework

Sample of points

- The trajectory is described as a finite collection of triplets

$$\Gamma_i : \{p_{is} | p_{is} = (x_{is}, y_{is}, t_s)\}, t_s = [t_0, t_1, ..., t_f]$$

- 3D Voronoi diagrams associated with the points
- Sequences of 3D Voronoi cells V_{is} are assigned to the sequence of points for each pedestrian

$$V_i = \{V_{is} | V_{is} = \{p | d_*(p, p_{is}) \leq d_*(p, p_{js})\}, \forall j\}$$

- $d_*(p, p_{is})$ - spatio-temporal assignment rule

Spatio-temporal assignment rules

Naive assignment rule

$$d_N(p, p_i) = \begin{cases} \sqrt{(p - p_i)^T (p - p_i)}, & \Delta t = 0 \\ \infty, & otherwise \end{cases}$$

Time-Transform assignment rules

$$\mathrm{d}_{TT_1}(p, p_i) = \sqrt{(x - x_i)^2 + (y - y_i)^2 + \alpha^2 (t - t_i)^2}$$

$$d_{TT_2}(p, p_i) = \sqrt{(x - x_i)^2 + (y - y_i)^2} + \alpha_i(t_i)|(t - t_i)|$$

$$d_{TT_3}(p, p_i) = \sqrt{(x - x_i)^2 + (y - y_i)^2 + \alpha_i^2(t_i)(t - t_i)^2}$$

α and α_i - conversion constants expressed in meters per second

Spatio-temporal assignment rules

Predictive assignment rule

$$d_P(p, p_i) = \begin{cases} \sqrt{(x_i + (t - t_i)v_i^x(t_i) - x)^2 + (y_i + (t - t_i)v_i^y(t_i) - y)^2}, & t - t_i \geq 0 \\ \infty, & otherwise, \end{cases}$$

$v_i^x(t_i)$,$v_i^y(t_i)$ - the speed of pedestrian i at t_i in x and y directions
$(x_i + (t - t_i)v_i^x(t_i), y_i + (t - t_i)v_i^y(t_i))$ - the anticipated position of the pedestrian at time t

Mahalanobis assignment rule

$$d_M(p, p_i) = \sqrt{(p - p_i)^T M_i (p - p_i)}$$

M_i - symmetric, positive-definite matrix that defines how distances are measured from the perspective of pedestrian i

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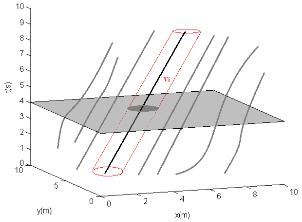
Voronoi-based traffic indicators

The set of all points in V_i corresponding to a specific time t

$$V_i(t) = \{(x(t), y(t), t) \in V_i\} \sim [m^2]$$



Density indicator

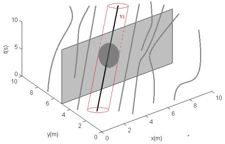
$$k(x, y, t) = \frac{1}{|V_i(t)|}, \text{ for } x, y \in V_i(t)$$

Voronoi-based traffic indicators

The set of all points in V_i corresponding to a given location x and y

$$V_i(x) = \{(x, y, t) \in V_i\} \sim [ms]$$

$$V_i(y) = \{(x, y, t) \in V_i\} \sim [ms]$$



Flow indicator

$$\vec{q}(x, y, t) = \begin{pmatrix} q^x(x, y, t) \\ q^y(x, y, t) \end{pmatrix} = \begin{pmatrix} \frac{1}{|V_i(x)|} \\ \frac{1}{|V_i(y)|} \end{pmatrix}$$

Velocity indicator

$$\vec{v}(x, y, t) = \begin{pmatrix} \frac{q^x(x,y,t)}{k(x,y,t)} \\ \frac{q^y(x,y,t)}{k(x,y,t)} \end{pmatrix} = \begin{pmatrix} \frac{|V_i(t)|}{|V_i(x)|} \\ \frac{|V_i(t)|}{|V_i(y)|} \end{pmatrix}$$

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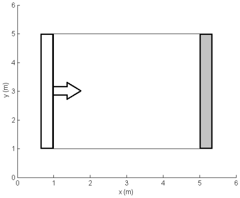
Synthetic data

Unidirectional scenario



- NOMAD simulation tool [Campanella, 2010]
- Population is assumed to be (approximately) homogenous in terms of walking speed
- Demand: 1.2 pedestrians/second

Characterization based on trajectories

Robustness with respect to the aggregation

- 100 sets of pedestrian trajectories synthesized for the described setting
- Indicators calculated for each set via 3D Voro and the standard Edie's method
- Hypothesis: the obtained distributions of the indicators represent the same population

Kruskal-Wallis test

Method	V-d_N	V-d_{TT_1}	V-d_{TT_2}	V-d_{TT_3}	V-d_P	V-d_M	*Edie*
p-value	1	1	1	1	1	1	$5.28e^{-13}$

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Characterization based on sampled data

Robustness with respect to the sampling frequency

- The samples of points from the synthetic trajectories obtained using different sampling frequencies
- Indicators calculated via
  1. 3D Voro applied to the trajectories obtained using the interpolation of the points
  2. 3D Voro applied directly to the samples
- Comparison of the indicators at 1000 randomly selected points to the corresponding values obtained utilizing true trajectories

Robustness with respect to the sampling frequency

High sampling frequency: $3.33s^{-1}$

Method	Mean		Mode		Median		90% quantile	
	IT	SoP	IT	SoP	IT	SoP	IT	SoP
3D Voro-d_N	$1.82e^{-02}$	/	0	/	0	/	$4.37e^{-02}$	/
3D Voro-d_{TT_1}	$2.12e^{-02}$	$2.00e^{-02}$	0	0	0	$8.10e^{-04}$	$1.02e^{-02}$	$1.08e^{-02}$
3D Voro-d_{TT_2}	$4.57e^{-02}$	$5.47e^{-02}$	0	0	$1.00e^{-04}$	$5.05e^{-03}$	$1.82e^{-02}$	$6.83e^{-02}$
3D Voro-d_{TT_3}	$5.61e^{-02}$	$8.60e^{-02}$	0	0	$4.30e^{-04}$	$1.33e^{-02}$	$1.78e^{-02}$	$9.83e^{-02}$
3D Voro-d_P	$9.44e^{-02}$	$1.31e^{-01}$	0	0	$1.25e^{-03}$	$1.33e^{-02}$	$1.95e^{-02}$	$1.20e^{-01}$
3D Voro-d_M	$3.47e^{-02}$	$8.57e^{-02}$	0	0	$8.80e^{-04}$	$2.09e^{-02}$	$1.80e^{-02}$	$1.28e^{-01}$
Edie	$1.05e^{-01}$	/	$2.50e^{-02}$	/	$5.00e^{-02}$	/	$2.38e^{-01}$	/

Low sampling frequency: $0.5s^{-1}$

Method	Mean		Mode		Median		90% quantile	
	IT	SoP	IT	SoP	IT	SoP	IT	SoP
3D Voro-d_N	$1.78e^{-01}$	/	0	/	$1.32e^{-01}$	/	$3.51e^{-01}$	/
3D Voro-d_{TT_1}	$4.23e^{-01}$	$3.85e^{-01}$	$1.25e^{-02}$	$2.83e^{-03}$	$1.11e^{-01}$	$8.54e^{-02}$	$4.79e^{-01}$	$4.14e^{-01}$
3D Voro-d_{TT_2}	$2.29e^{-01}$	$1.90e^{-01}$	$1.27e^{-02}$	$2.83e^{-03}$	$1.24e^{-01}$	$8.75e^{-02}$	$4.54e^{-01}$	$3.95e^{-01}$
3D Voro-d_{TT_3}	$2.77e^{-01}$	$2.49e^{-02}$	$1.73e^{-02}$	$4.36e^{-03}$	$1.32e^{-01}$	$8.82e^{-02}$	$4.70e^{-01}$	$4.38e^{-01}$
3D Voro-d_P	$2.79e^{-01}$	$2.73e^{-01}$	$1.88e^{-02}$	$2.05e^{-02}$	$1.23e^{-01}$	$9.51e^{-02}$	$4.71e^{-01}$	$3.99e^{-01}$
3D Voro-d_M	$2.46e^{-01}$	$2.73e^{-01}$	$3.37e^{-02}$	$6.38e^{-02}$	$1.43e^{-01}$	$1.00e^{-01}$	$4.99e^{-01}$	$4.66e^{-01}$
Edie	$6.37e^{-01}$	/	$1.13e^{-01}$	/	$5.63e^{-01}$	/	1.19	/

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Conclusion and future work

Conclusion

- A novel approach: data-driven discretization via 3D Voronoi diagrams
- Features number of desired properties
- Superior to existing methods
  - Robustness with respect to the aggregation
  - Robustness with respect to the sampling frequency

Future work

- Analysis of the performance for different scenarios
- Weighted assignment rules

Thank you

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