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Assessment of models for pedestrian dynamics with functional principal component analysis

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HIGHLIGHTS

- This version is enhanced according to the reviewer's comments.
- A paragraph to discuss force-based models in general was added.
- A paragraph to discuss the importance of validation and its nature was added.

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ABSTRACT

Many agent based simulation approaches have been proposed for pedestrian flow. As such models are applied e.g. in evacuation studies, the quality and reliability of such models is of vital interest. Pedestrian trajectories are functional data and thus functional principal component analysis is a natural tool to assess the quality of pedestrian flow models beyond average properties. In this article we conduct functional Principal Component Analysis (PCA) for the trajectories of pedestrians passing through a bottleneck. In this way it is possible to assess the quality of the models not only on basis of average values but also by considering its fluctuations. We benchmark two agent based models of pedestrian flow against the experimental data using PCA average and stochastic features. Functional PCA proves to be an efficient tool to detect deviation between simulation and experiment and to assess quality of pedestrian models.

1. Introduction

Many models for pedestrian dynamics were proposed in the past. Based on their properties different classifications of these models can be proposed. For a more comprehensive overview the reader is refereed to Refs. [1] and [2, Chap. 1].

Most of force-based models *qualitatively* describe the movement of crowds of pedestrians. Self-organization phenomena e.g., lane formations [3–5], oscillations at bottlenecks [3,4], clogging at exit doors [4,5] etc., are reproduced. From a physical point of view it is of interest how simple model reproduce qualitatively self-organization phenomena of driven multi-particle systems. That contributes to a better understanding of the investigated systems and the essential interactions. In

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addition numerical simulations basing of these models are used to address safety related issues, concerning e.g. design and conception of escape routes in buildings [6,7] or optimal organization of mass events or public transport facilities (VISWalk [8], Legion [9], …). For such utilization a thorough *quantitative* validation of the models is obligatory to ensure a reliable layout, dimensioning or evaluation of pedestrian facilities. In most known cases this is fulfilled by reproducing the fundamental diagram [10–13] or measuring the flow through bottlenecks [14,12,15]. An overview of quantitative validation of models by means of the fundamental diagram is given in Ref. [16].

Ongoing activities to formulate "benchmarks" for pedestrian dynamics models aim to define a set of verification and validation tests to assess the quality of used models [17,18]. Most formulated tests have the purpose to ensure in a general way realistic dynamics of pedestrians, e.g., pedestrians should not walk through walls or pedestrians should reduce their speed when their visibility is reduced.

On one hand, the common point between these quantitative methods is the fact that they are based on calculating specific traffic quantities, e.g. density, flow and velocity. On the other hand, these measurements are performed based on locally averaged values over time or space. Examples based on experiments showcasing the influence of the measurement method on the resulting empirical relations of such granular and heterogeneous systems of finite size are discussed in Refs. [19,20].

The differences between the measurement methods suggest that important information on the system may be lost during the measurement process. Moreover state of the art models describe pedestrian dynamics on a more detailed level by simulating trajectories of every single pedestrian allowing in principle a validation method assessing average pedestrian or traffic flow behavior, but also accounting for the amount and typical nature of fluctuation around this average.

A first methodology based on exploiting information of individual trajectories was introduced in Ref. [21] to calibrate the social force model. One virtual pedestrians interacts for a certain period of time with pedestrians assigned the exact positions and velocities extracted from experimental trajectories. By means of an evolutionary algorithm the deviations of the resulting trajectories from the experimental ones was used to calibrate the parameters of the model. But this approach does not allow an assessment of the quality of a model.

While an abundance of agent-based models in the field of pedestrian and traffic dynamics were developed in the last years [22,23] the question of systematic comparison of experimental evidence and model generated results has not caught the same attention. This would however be important for the ranking of models into more or less adequate ones. As argued above methodology of the evaluation should provide a comparison of model results and empirical data corresponding to the level of detail of the model. It is desirable that such a validation method should not only be able to assess average pedestrian or traffic flow behavior, but also account for the amount and typical nature of fluctuation around this average.

Among the difficulties in this validation process is the fact that in agent-based pedestrian or traffic flow data is functional, i.e. to each individual we associate data in the infinite dimensional space of trajectories $x(t)$. The adequate statistical approach for the study of pedestrian or traffic flow data is thus the well established method of functional data analysis [24]. In this method, the variation in the trajectories of different agents is interpreted as random fluctuations. Thus, the measured or simulated trajectories are interpreted as realizations of some stochastic process $X(t) \in \mathbb{R}^2$, where t stands for a time parameter and $X(t) = X(t, \omega)$ tacitly depends on some random parameter ω from a probability space $(\Omega, \mathcal{A}, P)$. For more details the reader is conferred to Ref. [25]. Although there are infinitely many trajectories available for an agent to move from point *A* to point *B*, it often turns out that a few typical modes of variation around the average movement are responsible for the bulk of fluctuation of trajectories between different individuals. As a classical method in the analysis of functional data, the functional principal component analysis (PCA) is the standard method to find and analyze these typical variations.

The scope of this article is to use functional PCA analysis to study the performance of agent-based models of pedestrian motion with respect to experimental data. In order to demonstrate the methodological approach, two models – social force model (SFM) [3] and generalized centrifugal force model (GCFM) [12] – are used to simulate pedestrian movement through a bottleneck of the same dimensions. In the following we apply functional PCA using the open source extension `fda` by Ramsey, Hooker and Graves [26] to conduct the analysis. We present the results and give a detailed comparison of average values for locations and velocities and their respective principal components. For the latter we separately compare strength, distribution of total variation, and morphology of principal components.

We show that functional PCA in fact can be used to make statistically significant statements about model quality. Functional PCA reveals significant deviation between both models and the experiment already on the level of average values. While the morphology of principal components for locations is more or less adequately represented by both models, there are significant deviations in the strength of fluctuations around the mean behavior with the GCFM model underestimating the experimentally observed fluctuations while the SFM mostly overestimates fluctuation strength. These empirical observations can be confirmed with statistical testing for significance using the PCA-bootstrap methodology [27,28].

In this article, for the first time we combine functional PCA in the sense of Ref. [24] with the bootstrapping of scores in order to calculate the fluctuations of specific statistics that describe and distinguish characteristic features of fluctuations of individual pedestrian behavior in a crowd. Also on the PCA-side, benchmarking and testing with specific statistics evaluated in functional PCA is a new strategy, to the best of our knowledge.

The article is organized as follows. In Section 2 we review the pedestrian flow experiment [29] as the benchmark case for this study. Section 3 gives a brief account on the SFM and the GCFM model. In Section 4 reviews the functional PCA and its numerical implementation. Section 5 is the main part of this article. After some introductory remarks on data formatting and smoothing (Section 5.1), we compare average data for x and y position data (Section 5.2) and velocities directed in the main direction of motion, which is the x-direction. We then compare fluctuations strength via PCA eigenvalues