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Continuum modelling of pedestrian flows: From microscopic principles to self-organised macroscopic phenomena

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HIGHLIGHTS

- State-of-the-art macroscopic model with global and local route choice behaviour.
- Multi-class continuum modelling based on microscopic modelling principles (i.e. social forces model).
- Derivation of explicit relation for equilibrium speed and walking direction.
- Reproduction of self-organised phenomena, such as dynamic lane formation, and formation of diagonal stripes.
- Preliminary results show model's ability to also reproduce phase transitions.

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ABSTRACT

The dynamics of pedestrian flows can be captured in a continuum modelling framework. However, compared to vehicular flow, this is a much more challenging task. In particular the integration of flow propagation and path choice are known to be problematic. Furthermore, pedestrian flow is characterised by different self-organised phenomena, such as the formation of dynamic lanes and diagonal stripes, which have not yet been captured in a continuum modelling framework.

This contribution puts forward a novel multi-class continuum model that captures some of the key features of pedestrian flows. It considers path choice behaviour on both the strategic (pre-trip) and tactical (en-route) level. To achieve this, we present a methodology to derive a continuum model from a microscopic walker model, in this case the social forces model. In doing so, we show that the interaction term present in the social forces model introduces a local path choice component in the equilibrium velocity.

Having derived the model, we analyse its properties both by means of mathematical analyses and simulation studies. This reveals the general behaviour of the model, as well as the ability of the model to reproduce self-organised structures, and phase transitions. To the best of our knowledge, this is the first continuum model that is able to reproduce these self-organised structures.

1. Introduction

Understanding, reproducing and predicting pedestrian flows is an important challenge that requires our attention in order to solve urgent societal problems in station design, pedestrian flow routing in airports, optimal evacuation planning

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and operations in sport stadiums, or in large vessels, crowd management, etc. The field of pedestrian flow or crowd simulation is, however, not as mature as its vehicular flow counterpart. On the one hand, this is because the field is relatively young. On the other hand, pedestrian flow operations are much more complex. This is not only due to the fact that a pedestrian flow is – at least – two-dimensional, while vehicular flows are by and large one-dimensional, but also due to the fact that in the flow dynamics operations and route choice levels are much more interwoven. On top of this, empirical and experimental investigations show that pedestrian flows feature complex dynamics, such as the self-organisation of spatio-temporal structures in bi-directional flows (lane formation) and crossing flows (diagonal stripes).

The pedestrian flow modelling playing field – in particular those models that have made it to the engineering practise – has been dominated by microscopic models, such as the social-forces model of Helbing and Molnar [1]. Few macroscopic or continuum models have been put forward that capture the core properties of pedestrian flows, which implies that large scale applications have not benefited from the advantages of macroscopic models. Furthermore, with the advent of new technology to monitor pedestrians and pedestrian flows, the need for analytical (macroscopic) frameworks allowing for state-estimation by, for instance, Kalman filters, is increasing.

This contribution puts forward a new continuum model that captures some of the key characteristics of a pedestrian flow, while including only few parameters. The article continues with a literature review (Section 2) The multi-class model is derived from a microscopic model (Section 3), and reproduces plausible state-space solutions (equilibrium speeds), and self-organised spatial temporal patterns (Section 4). Having presented the results of the mathematical analyses and simulations, we review the key findings of this contribution (Section 5).

2. Literature review

In this section, we review some of the key studies that form the foundation of the model presented in this manuscript. While not trying to be complete, we briefly present relevant empirical studies, as well as the main modelling approaches that have been put forward, with an emphasis on continuum models. In particular the latter type of models will be discussed in more detail, focusing on their ability to reproduce aforementioned pedestrian flow phenomena.

2.1. Empirical features

In the past decades, characteristics of pedestrian flow have been studied empirically and experimentally. These studies revealed many interesting features, including the existence of a fundamental relation between density and flow and self-organised structures. In this section, we briefly discuss some of these characteristics relevant for the topics discussed in this contribution.

The fundamental relation reflects the statistical relation between density ρ and (absolute) flow Q or speed V, i.e. $V = V(\rho)$ or $Q = \rho \cdot V = Q(\rho)$; see Ref. [2]. Many factors influence the shape of the fundamental diagram: for instance, [3] shows how cultural differences influence the shape of the fundamental relation; the capacity, the jam density and the shape of the fundamental diagram are also influenced by factors such as trip purpose and the heterogeneity of the pedestrians [4].

Next to the fundamental relation between density and flow, pedestrian dynamics are characterised by different self-organised phenomena. Self-organisation is defined as the spontaneous occurrence of qualitatively new behaviour through the non-linear interaction of many objects or subjects [5] without the intervention of external influences [6].

The most common self-organisation movement is lane formation [7]. During this process a number of lanes of varying width form dynamically in a corridor. Next to lane formation in bi-directional flows, diagonal stripe formation in crossing flows has been observed; e.g. see Ref. [7].

During their research at the Jamarat bridge Helbing et al. [4] found stop & go waves. These are temporarily interrupted longitudinally flows that appear at higher densities in uni-directional crowds. In an even more dense flow regime, turbulent flows were found. In this regime a pedestrian has no control over its own movements anymore. Local force based interactions between pedestrian bodies are seen.

Three other effects have been described at an operational level, namely herding [8], the zipper effect [9] and the faster-is-slower effect [5]. The first effect describes the case where unclarity of the situation causes individuals to follow each other instead of taking the optimal route. This behaviour is predominantly seen during stressful evacuation situations. The zipper effect describes the situation in which individuals allow others within the territorial space diagonally in front of them, as long as the direct space in front of their feet is still empty. It allows for narrower lanes in a bottleneck than expected based on the width of a pedestrians territorial zone. The third effect (Faster-is-Slower) describes a situation where the density in a queue upstream of a bottleneck is increasing, due to the fact that people keep heading forward while the bottleneck is clogged. The higher densities cause coordination problems since a large number of individuals is competing for a few small gaps. Bodily interaction and friction slow down the total crowd motion.

2.2. Modelling approaches

In a recent study, a comparison of pedestrian flow modelling approaches were cross compared, focusing on how these models are able to simulate the key phenomena indicated in the previous paragraphs [10]. The paper discusses different types of models, such as cellular automata, social force models, velocity-based models, continuum models, hybrid models,

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