Physica A 421 (2015) 594–604

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

The effect of stepping on pedestrian trajectories

Michael J. Seitz [a,b,*], Felix Dietrich [a,b], Gerta Köster [a]

[a] Munich University of Applied Sciences, Germany
[b] Technische Universität München, Germany

HIGHLIGHTS

- We present a model for pedestrian dynamics based on natural stepping of humans.
- Parsimonious utility functions express the desire to keep distances to walls and other pedestrians.
- The findings from controlled experiments serve for the calibration of the model.
- Increased speed yields smaller angles in change of direction.
- A simulation study of a bottleneck scenario validates the model's behaviour.

ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 3 November 2014
Available online 9 December 2014

Keywords:
Pedestrian dynamics
Simulation
Controlled experiments
Stepping behaviour
Empirical

ABSTRACT

The natural biomechanical motion process of many animals is stepwise. This feature of human movement and other bipeds is largely ignored in simulation models of pedestrians and crowds. We present a concise movement model for pedestrians based on stepwise movement. A series of controlled experiments was conducted to calibrate the model based on individual behaviour of pedestrians. We find that a change of direction is constrained by the current walking speed: the higher the speed the smaller the possible change of direction. Additionally, we present the trajectories and distances subjects held to a wall when walking around a corner. We use this result as a parameter for the simulation model. Finally, we validate the model's behaviour with an egress scenario with a corridor as bottleneck. The resulting trajectories show behaviour that has been found in controlled experiments with similar set-ups: if there is enough space, individuals try to walk in the middle of the corridor, but when a congestion is present multiple lanes form allowing for higher pedestrian flow. The model separates the behavioural aspects from biomechanical movement thus facilitating expandability and allowing experts to focus on their respective fields of expertise.

1. Introduction

Bipedal locomotion has a long and important history in the evolution of hominids. Pedestrian dynamics and crowd movements are part of our daily routine and have largely shaped public transportation, buildings and urban spaces [1]. The study of pedestrian behaviour and its impact is essential for designing these systems [2,3]. The biomechanical movement of pedestrians can have a direct impact on building structures and must be considered in their design [4,5]. Moreover, insights

* Correspondence to: Lothstr. 64, 80335 Munich, Germany. Tel.: +49 89 1265 3762; fax: +49 89 1265 3780.
E-mail address: m.seitz@hm.edu (M.J. Seitz).

http://dx.doi.org/10.1016/j.physa.2014.11.064
0378-4371/

into collective phenomena and collective behaviour are necessary for the analysis of infamous crowd disasters around the world that have led to the loss of many lives [6,7]. Therefore, modern concepts of crowd behaviour are important for the planning of public spaces and the training of professionals who have to coordinate events.

Self organisation and collective behaviour can be observed in many biological systems [8]. The effects of sociality on collective motion has been studied in animals, such as ants [9,10] and fish [11]. For humans, collective motion has been experimentally investigated using concepts such as consensus decision making [12] and social information [13]. In social psychology, collective behaviour is described as a group having a salient social identity and acting according to the social norms of that group [14,15]. While there is progress in understanding collective behaviour, there is still a lack of systematic quantitative data that would facilitate modelling all underlying mechanisms in crowd simulations.

However, some aspects of crowd motion have been investigated rather thoroughly [16] and suitable measurement methods have been developed [17,18]. One of the most basic characteristics is the density–speed relation [19–21]. Although it seems to differ over cultures and situations [22], it is a well established measure of crowd motion that can be used to calibrate simulation models. Another prominent phenomenon is the formation of lanes [23,24], which is suitable for qualitative validation [25].

Computer simulation has become an important tool to study these systems and the theories about them. It facilitates the quantitative and qualitative validation of mathematically formulated crowd models. Many approaches have been proposed for the simulation of pedestrian streams that capture some collective phenomena, especially for evacuation scenarios [26]. Force-based models are derived from the concept of attractive and repulsive potentials around a target, other pedestrians and obstacles [27–30]. Movement is indirectly modelled as acceleration as in Newtonian mechanics, with similar physical effects such as inertia. The social-force model has also been calibrated on individual level interactions [31]. A different class of models are cellular automata, which divide the plane into a grid of cells [32–36]. Pedestrians and obstacles are represented by occupied cells that cannot be stepped on. The simple structuring of space might seem convenient as discretisation and facilitates the computation of large crowds, but it leads to considerable artefacts in the motion of pedestrians. Another model explicitly formulates pedestrian decisions as cognitive process and uses a force-based layer for the physical motion [37].

Here we use a distinct model of locomotion based on the natural stepping behaviour of humans [38]. The next position is determined given the distance one can cover with one step, which is represented by a circle around the current position. The direction of motion is guided by functions, like potential fields in the social force model. However, in the model used in this paper the functions represent utility and the next position is determined through maximisation. Although it has been shown that people do not reason in accordance with general utility optimisation [39,40], we employ this concept for the decision layer because of its simplicity and validity of simulation outcome [38]. Furthermore, optimisation is locally bounded and the functions' parameters can be put in direct relation to pedestrian behaviour. With this stepwise model there are clear advantages over cellular automata, because of its independence of a grid and the natural discretisation [38]. Yet, it remains easy to implement, computationally efficient and expandable in a way that advanced modelling concepts can be carried over from cellular automata or social force models, such as small group behaviour [41].

The stepping behaviour of pedestrians has been largely ignored in crowd simulations so far, although it is the basis of movement for humans and other bipeds. The stepping of pedestrians can be investigated by controlled experiment and the results can be used for calibration of models that reflect this behaviour. Finally, the calibration of such a model with meaningful parameters from experiments is essential for its credibility in natural sciences.

The first focus of this work is the biomechanical layer of motion, that is, the stepwise movement and its constraints. The second focus is the choice of parsimonious utility functions for the model and their calibration according to the outcome of controlled experiments and the density–speed relation.

2. Methods

2.1. Simulation model

In this study, simulation scenarios consist of pedestrians, targets that pedestrians strive to reach and obstacles that pedestrians skirt on their way to the target (see Fig. 1). Choosing the next step on the way to the target is interpreted as a utility optimisation problem: there are different choices, that is, reachable positions nearby, and pedestrians choose the one with the highest utility value [42,36]. Thus, the utility function $u : \mathbb{R}^2 \to \mathbb{R}$ has to be defined for every position $x \in \mathbb{R}^2$ in the plane.

The utility function u_t for target attraction is represented by the negated arrival time of a propagating wave front that emanates from the target, moves at the same speed everywhere and flows around obstacles [43,44]. Mathematically this is obtained through the solution to the eikonal equation, which can be efficiently solved on a grid with the fast marching method [45]. Bilinear interpolation between grid points yields utility values for arbitrary points in the plane [44].

To avoid collisions and ensure a social distance between pedestrians, utility is deducted in close proximity to other pedestrians. This is realised by a function u_p. It models the body of a pedestrian as a hard shell with radius b. The social distance is modelled using the distance $d \in \mathbb{R}^+$ to another pedestrian's body: $d = \|x_i - x_j\| - 2b$, where x_i and x_j are the positions of the two pedestrians. Here we propose to use a function that has compact support and only two parameters w