Transportation Research Part C 37 (2013) 223–237

Contents lists available at SciVerse ScienceDirect

Transportation Research Part C

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

A hybrid multi-scale approach for simulation of pedestrian dynamics

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ARTICLE INFO

Article history:
Received 21 August 2012
Received in revised form 15 March 2013
Accepted 17 March 2013

Keywords:
Pedestrian dynamics
Navigation
Floor field
Hybrid model
Navigation graph
Route choice
Microscopic model

ABSTRACT

One of the most important aspects for a realistic prediction of pedestrian flows is the modelling of human navigation in normal situations such as early design phases of buildings or transportation systems and hubs as well as in evacuation studies to enhance safety in existing infrastructures. To overcome the limitations of current navigation models, this paper proposes a new hybrid multi-scale model, which closely links information between the small-scale and large-scale navigation layer to improve the navigational behaviour. In the presented hybrid navigation model, graph-based methods using visibility graphs are used to model large-scale wayfinding decisions. The pedestrians' movements between two nodes of the navigation graph are modelled by means of a dynamic navigation field. The navigation field is updated dynamically during the runtime of the simulation, explicitly considering other pedestrians for determining the fastest path.

The proposed hybrid approach provides a realistic modelling of human navigational behaviour and thus a realistic prediction of flows since it reflects the human cognitive processes triggered by wayfinding tasks. This includes taking into account other pedestrians for routing decisions who are visible from the current position of the considered pedestrian. The paper discusses the concept and the technical details of the proposed hybrid multi-scale approach in detail and presents an extensive case study demonstrating its advantages.

1. Introduction

Studying emerging phenomena in pedestrian crowds is a classical subject in complexity science. Due to an improvement of algorithms as well as computational power, the simulation of pedestrian dynamics has attracted many researchers in the fields of safety and transportation science. On the one hand, pedestrian flow simulations are used for virtual evacuation studies (e.g. Lämmel et al., 2010; Klüpfel et al., 2004; Rodriguez and Amato, 2010; Teknomo and Fernandez, 2012; Guo et al., 2011) and the proposal of corresponding optimal strategies (Hamacher and Tjandra, 2002) to enhance the safety of events and buildings.

On the other hand, simulation of pedestrian flows is an emerging topic in the early design phase of public transport systems, public transport hubs (Pelechano and Malkawi, 2008; Zhang et al., 2008) such as stations (Ding et al., 2011) or even large infrastructures and urban areas (e.g. Loscos et al., 2003; Haklay et al., 2001) as well as their safety (Shi et al., 2012) and operation (Rindsfüser et al., 2007). Of course, the utility of such virtual approaches depends crucially on the realism as well as on the computational speed of virtual approaches (Pelechano and Malkawi, 2008). If the realism of simulations

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http://dx.doi.org/10.1016/j.trc.2013.03.005

is not sufficiently accurate, e.g. appearance of unnatural congestions, prediction of the simulations would yield improper designs. At the same time, if computations take too long, virtual approaches can hardly be used for design studies and design optimisation.

From a conceptual point of view, models of pedestrian flows can be divided into microscopic models, simulating the behaviour of single pedestrians and their interaction, and macroscopic models, considering flows of pedestrian entities. Thus, being interested in local small-scale behaviour of pedestrian flows, microscopic models are the approach of choice. They can be distinguished into force models (e.g. Burstedde et al., 2001; Klüpfel, 2003; Kretz and Schreckenberg, 2006; Chraibi et al., 2011a), discrete-choice models (e.g. Antonini et al., 2006; Robin et al., 2009; Hoogendoorn and Bovy, 2004; Guo and Huang, 2012) or agent-based models (e.g. Rindsfüser et al., 2007; Dijkstra et al., 2006; Ronald et al., 2007).

To study large-scale behaviour and large scale navigation, macroscopic models are typically preferred like network-based models (e.g. Hamacher and Tjandra, 2002; Mitchell and MacGregor Smith, 2001) or fluid dynamics models (e.g. Henderson, 1974; Helbing, 1992). Very often one is interested in local phenomena, e.g. the evolution of congestions, which are induced by large scale navigation, e.g. many people are choosing the same route.

This challenge, bridging the gap between small-scale and large-scale aspects can be resolved using multi-scale models, e.g. combining graph-based approaches either with force models (e.g. Wagoum et al., 2012; Kretz et al., 2011) or with agent type models (e.g. Funge et al., 1999; Reynolds, 1999; Rindsfüser et al., 2007; Lerner et al., 2007; Sud et al., 2008; Teknomo, 2008; Asano et al., 2010; Dijkstra et al., 2006; Ronald et al., 2007).

However, these multi-scale models typically combine microscopic and macroscopic models in a very simplistic fashion. Thus the limitations of small-scale (e.g. being short-sighted) and large scale (e.g. not considering other moving pedestrians for route choice decisions) are usually not resolved. Information between the layers is not exchanged from the microscopic layer to the macroscopic layer and vice versa. Typically, the macroscopic layer provides the next intermediate destination to pedestrians steering in the microscopic layer and no information sharing between the microscopic and the macroscopic layer takes place.

The focus of the paper is the combination of advanced microscopic navigation strategies with macroscopic navigation strategies. Both state-of-the-art concepts alone including their qualitative properties, especially their realism with respect to real world scenarios, have been studied extensively in the literature. Combining both concepts, the realistic qualitative properties are inherited but the drawbacks of microscopic navigation concepts (extensive computation times) and macroscopic navigation strategies (difficulty to estimate travel times) are resolved.

We propose a new holistic multi-scale model unifying the advantages of the single layers and overcoming their limitations. Information is shared between the layers, such that the above mentioned issues are resolved. At the same time the approach allows an efficient realisation from a computational point of view. We demonstrate this new approach by extending a well established cellular automaton model (Köster et al., 2010). However, the concepts can be easily generalised to other microscopic pedestrian simulators. Due to computational efficiency as well as its high degree of realism, we believe that the developed concepts provide a valuable tool for optimising transportation systems, buildings, as well as large infrastructures such as transportation hubs or even urban areas.

This article is structured as follows: First, we review existing multi-scale models in Section 2 and outline their limitations. Section 3 describes in detail the construction and implementation of each layer. In Section 4 the combination of these layers is explained. To show the improvements in the simulation results, various tests have been conducted and are presented in Section 5. A discussion concludes the article.

2. State of the art and limitations of multi-scale models

Multi-scale models typically consist of two layers: a small-scale layer modelling the navigation of pedestrians to a designated destination and a large-scale layer modelling strategic navigation, i.e. choosing different (intermediate) destinations.

On the small-scale layer, pedestrians are steered to a designated destination by forces similar to Newtonian particle mechanics. Typically, these forces are modelled using an attractive force or potential-based approach. Assuming a conservative force, i.e. the local force is given by the gradient of the potential, both approaches basically coincide. Continuous social force models (e.g. Helbing and Molnár, 1995; Lakoba et al., 2005; Löhner, 2010; Parisi et al., 2009; Chraibi et al., 2010; Chraibi et al., 2011b; Yu et al., 2005) typically use a force-based description whereas cellular automata, i.e. space-discretized models, typically rely on a potential-based description.

In the following, we will restrict ourselves to a potential-based cellular automaton model (Köster et al., 2010), which can be always interpreted in a force-based description assuming that forces are given by the gradients of the corresponding potentials. In the potential-based approach, a pedestrian's movement towards the destination is realised by a decreasing potential value towards the direction of the destination. Obstacles and other pedestrians walking in the vicinity of the pedestrian are considered via a repulsion force or repulsion potential (e.g. Kretz and Schreckenberg, 2006; Chraibi et al., 2011a; Köster et al., 2010) and thus added to the potential value. Typically, it is assumed that single pedestrians have a repelling potential of a certain width, which might also have a certain spatial structure depending on the direction of movement (Klüpfel, 2003; Köster et al., 2010). Using a cellular automaton, these pedestrians can be detected very easily in the nearby surrounding by simply checking neighbouring cells. The potential-based steering behaviour is often referred to as floor field or navigation field based behaviour and a variety of approaches to construct corresponding potential fields have been pro-