Transportation Research Part A 86 (2016) 159–176

Contents lists available at ScienceDirect

Transportation Research Part A

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

A hybrid simulation-assignment modeling framework for crowd dynamics in large-scale pedestrian facilities

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ARTICLE INFO

Article history:
Received 2 December 2013
Received in revised form 6 January 2016
Accepted 22 February 2016

Keywords:
Crowd dynamics
Simulation models
Networks
Cellular automata
Pedestrian flow

ABSTRACT

This paper presents a hybrid simulation-assignment modeling framework for studying crowd dynamics in large-scale pedestrian facilities. The proposed modeling framework judiciously manages the trade-off between ability to accurately capture congestion phenomena resulting from the pedestrians' collective behavior and scalability to model large facilities. We present a novel modeling framework that integrates a dynamic simulation-assignment logic with a hybrid (two-layer or bi-resolution) representation of the facility. The top layer consists of a network representation of the facility, which enables modeling the pedestrians' route planning decisions while performing their activities. The bottom layer consists of a high resolution Cellular Automata (CA) system for all open spaces, which enables modeling the pedestrians' local maneuvers and movement decisions at a high level of detail. The model is applied to simulate the crowd dynamics in the ground floor of Al-Haram Al-Sharif Mosque in the City of Mecca, Saudi Arabia during the pilgrimage season. The analysis illustrates the model's capability in accurately representing the observed congestion phenomena in the facility.

1. Introduction

Large-scale pedestrian facilities are an integral and increasingly important component of the urban built environment. Examples of these facilities include exhibit and convention halls, worshipping halls, stadia and sport arenas, transit terminals, and amusement parks, to name a few. During their peak periods, these facilities serve tens or even hundreds of thousands of pedestrians, experiencing severely congested conditions that are vulnerable to the occurrence of catastrophic accidents (Still, 2010). These accidents have brought more attention to the design and the operation management process of these facilities to ensure safe and efficient operation during both normal and extreme operating conditions. Thus, modeling tools that are capable of analyzing crowd dynamics in these facilities at a high fidelity level are critical to accomplish these tasks. These modeling tools provide a platform to depict areas of deficient capacity and unsafe movement conflicts (e.g., bottlenecks), and thus help identify ways to improve system design, and develop efficient crowd management schemes under different operational scenarios. Essential capabilities that these tools should provide include: (1) detailed depiction of the architectural blueprint of the facility considering connectivity among its spaces, entrance and egress gates, and any

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http://dx.doi.org/10.1016/j.tra.2016.02.011
0965-8564/

existing obstacles; (2) accurate representation of the crowd dynamics and associated congestion phenomena resulting from the pedestrians' movement behavior and the surrounding environment; and (3) capturing the effect of crowd control strategies that might be adopted as part of proposed crowd management schemes.

Considerable effort has been devoted to developing modeling tools that can be used to study pedestrians in crowded facilities. These tools vary in the trade-off level they provide between *fidelity*, i.e., the ability to accurately capture congestion and crowd behavioral phenomena, and *scalability* to represent large facilities with complex architecture and high pedestrian demand levels (e.g., densities of 4 persons/m^2 and above). Inadequate consideration of such trade-off could result in modeling tools that are either nominally capable of representing large-scale facilities while failing to accurately capture specific congestion phenomena that might occur in these facilities at high demand levels, or tools that are successful in representing the congestion phenomena with limited ability to scale up to large facilities (Sarmady et al., 2007; Tunasar, 2013; Duives et al., 2013). As discussed in the next section, most existing models fall in the latter category.

Applications of most existing models to large facilities with intensive demand levels have been achieved by reducing the size of the modeled area, truncating the analysis horizon, or through a combination of both (Sarmady et al., 2007; Tunasar, 2013). Unfortunately, arbitrarily reducing the size of a modeled space could limit the ability to study the impact of congestion in adjacent spaces with potential flow spillback. Furthermore, truncating the analysis horizon could preclude reaching steady-state conditions, which is essential especially for capacity estimation studies.

This research is motivated by the need for a modeling framework to study crowd dynamics in large-scale (mega) pedestrian facilities that are characterized by complex architectural design with multiple connected spaces, intricate pedestrian movement patterns, and extreme congestion. In this research the term "crowd" refers to a large number of persons that are temporarily gathered closely together; responding to common stimuli and engaged in various forms of collective behavior. The term "congestion" refers to a state of overcrowding and space that is filled with more people than is desirable. The desirable level could be defined by the crowd themselves or by the facility operators.

This research contributes to the existing literature by introducing a new modeling framework that judiciously manages the trade-off between ability to accurately capture congestion phenomena resulting from the pedestrians' collective behavior, and scalability to model large facilities. The framework integrates a dynamic simulation-assignment logic with a hybrid (two-layer or bi-resolution) representation of the facility. The top layer consists of a network representation of the facility, which enables modeling the pedestrians' route planning decisions while performing their activities. The bottom layer consists of a high resolution Cellular Automata (CA) system for all open spaces, which enables modeling the pedestrians' local maneuvers and movement decisions at a high level of detail. Accordingly, the paper contributes primarily through providing (1) hybrid, bi-resolution modeling approach and system representation, (2) ability to address both tactical-level pedestrian path choices as well as embedded operational-level behaviors in density levels that may attain extreme levels, (3) improved agent interaction mechanisms in dense crowds that provide realistic representation of observed phenomena, (4) application to actual system with very high demand levels and associated densities, and (5) validation against actual observation.

The framework is applied to estimate the capacity and other performance measures under a typical operational scenario of the core area of Al-Haram Al-Sharif Mosque complex in Makkah, Saudi Arabia, which is a uniquely challenging facility for crowd modeling applications (Sarmady et al., 2007; Tunasar, 2013). It serves millions of pilgrims who perform several rituals that require complex maneuvers under extreme congestion situations. The mosque consists of the main hall, which is surrounded by a multi-story building and another additional open area. It has a total capacity of 400,000 worshipers and is expected to increase to one million worshippers after an ongoing expansion. At the center of the main prayer hall, a cube-shaped shrine building known as "Al-Ka'aba Al-Mosharafa" is located. During the Hajj event, each of the nearly three million pilgrims has to visit the Mataf system, at least twice, to perform the "Tawaf" ritual. The Tawaf is a circumambulation process whereby pilgrims go around Al-Ka'aba a total of seven times in the counter-clockwise direction, starting from a predefined point (line that emanates along a radius from the center of Al-Ka'aba). During circumambulation, each pilgrim tries to come closer to Al-Ka'aba, in the hope of reaching and touching it, and also to avoid circumambulation in larger-radius loops. Upon finishing the Tawaf, pilgrims try to find a way out of the system, causing notorious crowd conflicts with other entering and looping pilgrims. The facility usually encounters high level of density of 8 persons/m^2, with pilgrims expect to walk at relatively lower speed with humbleness and modesty (Curtis et al., 2011). The crowd consists of a heterogeneous set of pilgrims, varying with respect to activity, walking speed, and congestion perception. All these factors make the facility unique and accordingly the results of this application should not be generalized to other facilities.

The next section provides a review of existing models with focus on simulation approaches and applications. Detailed description of the proposed modeling framework is then presented, including the bi-resolution approach used to combine network-based routing and activity implementation of pedestrians, with the complex interactions taking place in the flow systems. The formulation of the models and specification of the behavioral interaction mechanisms that comprise the modeling framework are also discussed. The model application is then provided. Finally, concluding remarks along with possible extensions of the research work are given.

2. Literature review

The literature reports numerous models that differ in their application scope, underlying theoretical approach, required effort for calibration and validation, and scalability. For example, applications of existing models include modeling