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A network optimization-based approach for crowd management in large public gatherings

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ABSTRACT

Effective crowd management during large public gatherings is necessary to enable pedestrians' access to and from the venue and to ensure their safety. This paper proposes a network optimization-based methodology to support such efficient crowd movement during large events. Specifically, a bi-level integer program is presented that, at the upper-level, seeks a reconfiguration of the physical layout that will minimize total travel time incurred by system users (e.g. evacuees) given utility maximizing route decisions that are taken by individuals in response to physical offerings in terms of infrastructure at the lower-level. The lower-level formulation seeks a pure-strategy Nash equilibrium that respects collective behavior in crowds. A Multi-start Tabu Search with Sequential Quadratic Programming procedure is proposed for its solution. Numerical experiments on a hypothetical network were conducted to illustrate the proposed solution methodology and the insights it provides.

1. Introduction

Effective management of pedestrian movement during large public gatherings can provide crucial support toward meeting pedestrian access and safety goals. Large public gatherings are held in a variety of venues, such as complex buildings, transportation stations, football stadiums, commercial malls, and other type of facilities. Poor execution of crowd management within these venues can frustrate the people in a crowd by thwarting their goals. At the extreme, poor crowd management has caused many instances of crowd crush, injuries and fatalities involving high volumes of people in a wide array of circumstances, ranging from rock concerts and sales events at stores to the offering of free food and clothing. A few specific examples where better crowd management may have saved lives include: the 1979 Who concert in Ohio in which 11 people perished, the 1989 UK Hillsborough Stadium sporting event where 96 deaths may have been prevented, 362 deaths resulting in the 2006 Hajj in Saudi Arabia, and the 2010 incident in Northern India where 63 people perished while seeking free food and clothing at a temple. In addition, in some circumstances, such as in the event of fire, explosion, occurrence of natural or human-induced disaster event, or crowd violence, well-designed systems for moving large crowds quickly are needed to support quick egress from dangerous situations.

The majority of works related to crowd management propose methods for modeling crowd movements during emergency evacuation. Such models can be used to quantify the performance, in terms of measures like evacuation time, of a

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given facility's architectural layout during such an event. These models can be broadly categorized as: fluid dynamics-based approaches (Colombo and Rosini, 2005; Hughes, 2002), optimization and network flow-based methods (Choi et al., 1988; Fahy, 1994), and simulation-based techniques, which include rule-based methods (Blue and Adler, 2001; Helbing, 1995), agent-based modeling (Shi et al., 2009) and virtual reality (Shih et al., 2000). Additional information can be found in Gwynne et al. (1999), Kuligowski and Peacock (2005) and Zheng et al. (2009). Other works, including for example (Hoogendoorn and Bovy, 2004), focus on simulation of pedestrian movement under non-emergency situations. Whether created to support analysis in emergency or non-emergency situations, techniques described in these works are designed for use in evaluation of, for example, architectural designs and other elements of the physical layout. They do not provide strategies for managing the crowd.

Techniques have been proposed to support crowd management. In the context of pedestrian movement, these techniques determine optimal routes to which pedestrians should be guided within an existing physical environment. Route guidance is created through network optimization-based methods. Simplistic, static methodologies based on minimum cost network flows have been developed (e.g. Yamada, 1996). More sophisticated techniques that capture problem dynamics, time-dependencies and other problem characteristics have been proposed specifically for building evacuation (Cai et al., 2001; Mamada et al., 2003). A variety of objectives have been considered, including for example maximizing throughput by a given end time (Miller-Hooks and Sorrel, 2008) and maximizing the minimum probability of arrival at an exit for any evacuee (Opasanon and Miller-Hooks, 2008). Other works have considered the role of real-time information in updating routing instructions (Miller-Hooks and Krauthammer, 2007). Chen and Miller-Hooks (2008) developed a dynamic network flow-based model that forces instructions to reflect how shared information will be used. A review of optimization techniques proposed for use in building and regional evacuation is provided in Hamacher and Tjandra (2002). Relevant network optimization-based techniques developed for regional evacuation are described in Kimms and Bretschneider (2011). Unlike the simulation and fluid dynamics-based methods that are used in modeling pedestrian movement, optimization-based techniques provide strategies for pushing flow through the network to achieve system optimal performance.

Related techniques have been proposed for use in guiding vehicular traffic in both emergency and nonemergency circumstances (see Kesting et al., 2008; Liu et al., 2007). Dynamic traffic management approaches, such as ramp metering, adaptive speed limits, and provision of real-time information, are widely used to support efficient vehicular traffic movement during peak traffic flow. These strategies are also used in emergency evacuation scenarios. Although tools developed for vehicular evacuation have relevance, there are significant distinctions in behavior and degrees of freedom between vehicular and pedestrian modes that make direct application of traffic tools insufficient for use in the pedestrian environment.

Approaches discussed thus far focus on influencing the movement of pedestrians through a given physical layout. An alternative might be to redesign the physical environment to facilitate pedestrian movement in pursuit of a particular goal. Such redesign can both limit pedestrian choice and enhance or restrict capacity along routes to facilitate efficient movement and prevent crowd crush or other unsafe situations. Changes to the physical layout might be achieved through opening or closing gates/doorways, placing or removing barriers or changing illumination intensity to coerce pedestrians along certain paths. No prior work has suggested such an approach in the context of pedestrian movement; however, redesign methodologies, such as the use of contraflow, have been proposed for evacuation by automobile (see Abdelgawad and Abdulhai, 2009) for a review.

In this paper, a network optimization-based methodology that seeks the optimal reconfiguration of a physical (architectural) layout to support efficient crowd movement during large events is proposed. This methodology takes into consideration pedestrian response to route offerings as controlled through the architectural design. Further, it incorporates findings from the social sciences and psychological studies on collective behavior in crowds (Aveni, 1977; Qiu and Hu, 2010). That is, the methodology recognizes that families, friends and emergent groups will act together, and control strategies that separate such groups will be ineffective. This approach seeks a system optimal solution based the crowd manager's goals; however, it explicitly recognizes the utility maximizing behavior of individuals in the crowd as is consistent with user equilibrium. In contrast to prior fluid dynamics-based techniques that model aggregate pedestrian flows, often requiring extraordinary computational effort to solve embedded differential equations, the proposed approach captures individual movements and goals with significantly reduced computational time. Alternative simulation-based methodologies offer an ability to replicate complex behaviors, but do not provide guidance; rather, they support performance assessment given chosen guidance mechanisms. The proposed technique builds on concepts of network optimization, but accounts for behavioral norms often only included in computationally expensive simulation-based approaches.

A bi-level integer program is presented that, at the upper-level, seeks a reconfiguration of the physical design that will minimize total travel time incurred by system users (e.g. evacuees) given route decisions that are taken by individuals in response to physical offerings in terms of the infrastructure at the lower-level. The lower-level formulation seeks a pure-strategy Nash equilibrium that respects group behavior. This mathematical program is presented in detail in Sections 3 and 4. This is preceded by a general overview of the approach in Section 2. In Section 5, the bi-level program is reformulated as a nonlinear integer single-level program for which determination of a globally optimal solution is formidable. Thus, a Multi-start Tabu Search with Sequential Quadratic Programming (MTS-SQP) procedure is proposed for its solution. This procedure is described in Section 6. Numerical experiments were conducted on a hypothetical example to assess this technique. Results of these experiments are given in Section 7. Conclusions and directions for future work are discussed in Section 8.