Modeling and Optimization of Crowd Guidance for Building Emergency Evacuation

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1 Introduction

Effective building evacuation in case of emergencies such as fires, chemical spills, or spreads of biological agents has long been recognized as an important issue, and effective crowd guidance can improve egress efficiency, occupant survivability, and mitigate or prevent undesirable consequences such as blocking or stampeding. To effectively guide crowds, however, is a challenging issue because emergency events may propagate in uncertain ways and affect the availability of egress paths; egress path capacities may constrain the speed of crowd movement; and crowd could be stressed making their behaviors different from their normal modes. Although good results have recently been obtained on microscopic behaviors of individuals such as the social force model of Helbing [1-3], there is a major gap between these microscopic models of individuals evacuating from rooms and the macroscopic models of crowd flows needed to evacuate them from a building. Most existing egress guidance methods assume that crowd behaviors are independent of emergency situations and are fully controllable under guidance. These assumptions make it difficult to capture important features such as stampeding or blocking.

2 The Probabilistic Graphical Model

To bridge the gap between microscopic and macroscopic crowd models, a probabilistic graphical model is established in this paper to characterize the nonlinear interactions among the states of the emergency events, crowd stresses, egress capacities, and crowd flow rates. As shown in Fig. 1, there are several major components in the model:

- There is a “desired flow rate” for an individual, similar to the “desired velocity” of Helbing et al. [1]. If an emergency becomes urgent, people become more impatient, and the desired flow rate increases in a probabilistic manner.
- If the aggregate desired flow rate of a crowd is smaller than the egress capacity of a passage, then the crowd flow rate is equal to the desired flow rate

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without blocking. However, if the aggregated desired flow rate is larger than the passage capacity, then the crowd flow rate decreases drastically in a probabilistic and nonlinear fashion, resulting in the "faster-is-slower" scenario of Helbing et al. [1], and eventually leading to blocking and stampeding.

- Whether an individual would follow guidance is probabilistic and depends on his/her trust on the guidance provided, and his familiarity with the evacuation paths and whether other people follow the guidance.

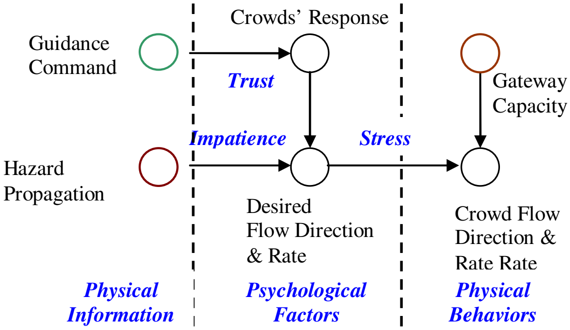

Fig. 1. The Probabilistic Graphical Model

This probabilistic graphical model incorporates two insightful psychological factors: impatience and trust, where impatience is the cause of blocking events, and trust reflects how crowds respond to guidance. An individual's trust in guidance evolves with how effective the guidance has been and affects one's egress direction. The high pressure derived from the state of the emergency event causes people to become impatient, and want to move through a passage fast, however, the actual flow rate is constrained by the passage capacity. If the desired flow rate is below the passage capacity, it can be achieved. The more it exceeds the capacity, the higher is the blocking probability, causing drastic decrease of the crowd flow rate. At a higher level, this model can be characterized by the energy balance concept, where the state of the emergency drives the desired flow rate and therefore the "Stress Energy." This stress energy is "balanced" between the "Static Energy" captured by the crowd density (affected by the passage capacity) and the "Dynamic Energy" represented by the flow rate. Such a macroscopic model thus provides a theoretical foundation for linking crowd stress behaviors to the situation, enables us to predict potential blockings in emergency evacuation, and provides a foundation to optimize crowd guidance.

3 The Overall Optimization Formulation

The above guided crowd behavior model can be combined with the egress network and the emergency event dynamics to form an optimization problem with the goal to evacuate as many people and as fast as possible while reducing the relevant risks through appropriate guidance of the crowds. The egress network can be modeled as a room-and-path structure by using a directed graph with egress path capacity constraints. Fig. 2 illustrates a sample room-and-path structure and how it is converted to a direct graph.

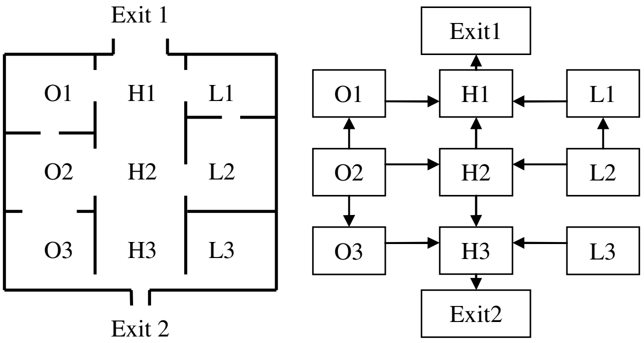

Fig. 2. An Egress Network

For the propagation of emergence events such as fire and smoke in buildings, many models have been established, including field models [4, 5]; NIST's Fire Dynamics Simulator [6]; and McGrattan et al. [7], zone models [8], and cellular automaton models [9, 10]. These models can simulate fire propagation in a building. In this paper, the fire propagation dynamics is simplified as a state transition model, where the transition is governed by conditional probabilities that fire propagates from one room to its "adjacent" rooms. The probabilistic graphical models, the egress network, emergency event dynamics, and crowd guidance then generate the crowd flow rates.

The goal of crowd guidance is to evacuate as many people and as fast as possible while reducing the relevant risks. This translates to maximizing a weighted sum of the expected number of total people evacuated, expected cumulative number of people evacuated, and the negative values of the corresponding semi-variances considered as a risk measure.

4 Solution Methodology

The problem thus formulated is a Markov decision problem, and to obtain an optimal solution, computation complexity is a major challenge. To reduce the computational requirements, Lagrangian relaxation is used. This is based on the insight that groups of crowds are mostly independent except when they compete for small passages, and such interactions are described by a set of nonlinear egress capacity constraints as described in Section 2. The problem is thus solved by using the "divide and conquer" approach. After the coupling nonlinear egress capacity constraints are "approximately relaxed" based on the sum of individual flow rates, individual group subproblems are solved by using stochastic dynamic programming with the rollout scheme [11]. Individual groups are then coordinated by the iterative updating of Lagrangian multipliers by using the surrogate subgradient method [12].

5 Numerical Testing Results

The above method has been implemented in Matlab and run on an Intel Core™2 Duo CPU with 2G memory for scenarios with fire as the emergency event. An example is tested where 50 people are evacuated in a structure of 6 rooms, a lobby area, 9 paths and 2 exits as depicted in Fig. 2. Two groups of evacuees are considered where Group 1 consists of 30 people locating in Office 3 initially; and Group 2 consists of 20 people locating in Lab 2 initially. A fire starts at Lab 3 and its propagation is based on a state transition model. For each discrete decision point we look ahead five time steps.

Fig. 3 shows the optimal paths at the initial time. These paths are obtained because the probabilistic graphical model foresees a potential blocking for the path from Office 3 to Exit 2. Thus Exit 2 is not used and people are guided to use Exit 1. At time 5, the guidance is updated due to fire propagating to the lounge area affecting the availability of the previous paths as shown in Fig. 4.

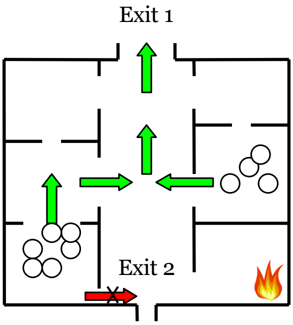

Fig. 3. Initial guidance at t = 1

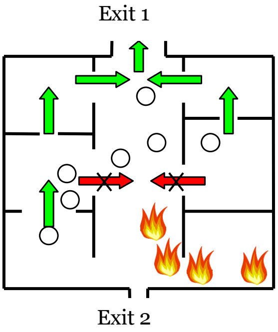

Fig. 4. Guidance updated at t = 5

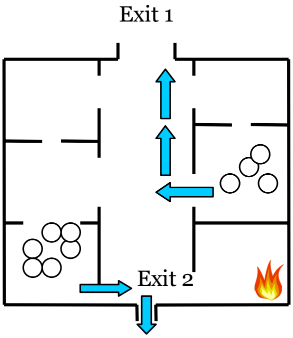

Fig. 5. Initial guidance ignoring nonlinear behaviors

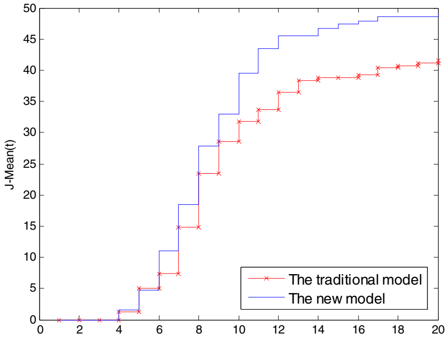

Fig. 6. Comparison of the new vs. the traditional methods

If the nonlinear crowd behaviors are not considered while other conditions remain the same, the guidance at the initial time is shown in Fig. 5 where Group 1 is guided to use Exit 2. However, this would lead to blocking as the crowd try to rush through the narrow passage of Exit 2, resulting in a much slower egress. The average objective functions of 25 Monte Carlo simulation runs are summarized in Fig. 6, showing the superiority of the new model and the method.

6 Conclusion

This paper investigates the crowd guidance problem for building emergency evacuation. A probabilistic graphical model is established to bridge the gap between microscopic models and macroscopic models while capturing the characteristics of crowd behaviors in emergencies. Then the guidance is obtained by using stochastic dynamic programming with rollout within the Lagrangian relaxation framework. Compared with results obtained by the traditional model, the guidance obtained by the new model can help prevent or mitigate potential blockings, improve evacuation efficiency, and manage risks. A different way to look at our approach is to provide crowds with expected times to safety as egress advices while considering crowd behaviors and the corresponding effects.

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