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Leader–follower model for agent based simulation of social collective behavior during egress

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ABSTRACT

There is growing consensus that individuals egressing during emergencies engage in social collective behavior that is ordered and cooperative. Despite this fact however, a great many of the existing models either do not account for this type of behavior or model it in an inadequate manner. In this paper, a leader–follower agent-based model is proposed to interpret local social interactions and collective behavior and then use this information to mimic three particular scenarios: lining up in counter-flow, queuing, and collective mobility. To achieve this, a pedestrian agent can establish informal and transient leader–follower relationships with others while adjusting its behavioral patterns as warranted by the situation. The proposed model is calibrated to existing field data and then validated using another set of field data, where it is shown that the new model is capable of reasonably simulating social collective behavior during egress.

1. Introduction

Dozens of egress models have been published over the past half century (Kuligowski, 2008). Aside from a few ones (e.g. MASSEgress (Pan, 2006) and SAFEgress (Chu and Law, 2012)), the vast majority of published models assume that evacuees are intent on leaving as quickly as possible without meaningful social interaction and adherence to cultural norms (Santos and Aguirre, 2004). To this end, models published prior to the early 2000s (Helbing et al., 2000) were commonly based on panic theory, which has since been discredited (Aguirre et al., 2011b). Some recent models still assume that competitive behavior dominates egress response (e.g. FDS + Evac, in Korhonen et al., 2010). Recent field work has shown that evacuees perform complex maneuvers (Challenger et al., 2009; Aguirre et al., 2011b) and behave deliberately rather than in a non-cooperatively competitive manner or mindless panic. Some of these studies show that social and social-psychological factors significantly influence pedestrians' movement (Santos and Aguirre, 2004; Moussaïd et al., 2010; Aguirre et al., 2011b). In particular, pedestrians can evacuate in an ordered and/or cooperative manner, and social collective behaviors are present and consequential during egress, rendering inappropriate the often-used practice of selecting the closest exit to describe egress behavior (Cialdini, 1993; Pan, 2006; Aguirre et al., 2011b; Chu and Law, 2012).

Counter-flow is a situation in which social collective behavior can occur. In counter-flow, groups of pedestrians walking in opposite directions meet head-on in a confined space. Field studies have shown that people form lines and follow an ad-hoc leader when pedestrian density is sufficiently high (Still, 2000; Schadschneider et al., 2009). Isobe et al. (2004) and Kretz et al. (2006) have conducted two independent experiments of counter-flow in narrow corridors. The former measured total passing time over the corridor, while the latter measured passing time through three locations. Both experiments showed a generally linear dependence of passing time on population size and automatic line forming during counter-flow was documented. Smith et al. (2009) improved the CrowdDMX (Langston et al., 2006) model's ability to represent counter-flow. Heliövaara et al. (2012) modified the FDS + Evac model (Korhonen et al., 2010) by assuming that right-hand road traffic rules govern a pedestrian's tendency to move in counter-flow situations.

Queuing and collective mobility are other examples of social collective behavior, for in them social and cultural emergence is common, as people have to learn to cooperate with strangers while being guided by new sets of social norms. When an emergency occurs, evacuees may not be fully aware of the extent of the hazard because they have not yet been alarmed by officials or by visible

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fire or smoke, for example. They thus start to egress in a relaxed manner and are under relatively low anxiety. They keep common cultural norms, for example by queuing up when congestion occurs before an exit or doorway. In contrast to competitive situations, queuing evacuees are considered to lead to more effective evacuation (Pan, 2006; Challenger et al., 2009). Collective mobility occurs when some evacuees are faced with uncertainties about what is going on and what they can do to protect themselves and others dear to them (Cialdini, 1993; Pan, 2006). For example, in a room with multiple egress points, evacuees who are uncertain about which way to move may choose to follow others who appear more deliberate in their actions.

Okazaki and Matsushita (1993) developed an agent-based model to simulate queuing behavior in a railway station. Pan (2006) also developed an agent-based model, implemented in a computer program called MASSEgress, which accounted for important egress behaviors including competitive, queuing, and collective mobility responses (termed herding). These behavioral patterns are controlled by several perception-related parameters, such as importance, uncertainty, urgency and stress level. In spite of its sophistication, MASSEgress has some drawbacks, for example, when modeling queuing behavior, only a single line is permitted to form regardless of the width of the doorway. Pelechano et al. (2007) developed another agent-based model termed HiDAC which enables agents to form wide or narrow queues in non-panic situations. Despite their sophistication, however, both models ignore the fact that evacuees are seldom detached actors but are instead members of groups that are evacuating even as the evacuee is also attempting to egress the place of danger.

Of the egress modeling techniques surveyed in Kuligowski (2008), Agent-Based Modeling (ABM) is among the most realistic and promising (Aguirre et al., 2011a). In ABM, evacuees are represented by autonomous entities (agents) that have their own characteristics, are adaptive and capable of socially and physically interacting with each other and with their environment (Fang et al., 2015). As such, ABM can potentially address some of the complex social and physical responses of individuals and groups of actors during egress situations and is selected as the research tool in this study.

In this paper, a leader–follower model is proposed and implemented in conjunction with the Scalar Field Method (SFM) presented by Fang et al. (2015) within an ABM framework. The original model is based on rationality theory (Aguirre et al., 1998, 2005, 2011b); it simulates the 'thinking' process of an agent faced with a complex network of relationships at the social level. The present version of SFM represents an important improvement upon previous versions of the model, which was unable to simulate some social collective behaviors such as queuing and collective mobility and had difficulty handling counter-flow conditions in dense crowding situations (Fang et al., 2015).

The extended version presented herein addresses these weaknesses by modifying different behavioral patterns as a function of a number of parameters including stress level, uncertainty, besieged in slow crowd or not, and status as a leader. The model enables an agent to form informal and temporary social relationships with other agents and to follow or become a leader when the conditions warrant it. Preliminary tests reveal the ability of the new model to simulate collective egress behavior, and matches field observations and experimental results. In the rest of this paper the theoretical background of SFM and the egress platform, social system and collective behavior are presented first. The follower behavior model and its implementation are then discussed, followed by a presentation of the model's development and its implementation. Finally, a series of validation and capability-demonstration simulations are presented.

2. Theoretical background

2.1. The Scalar Field Method (SFM)

The SFM, as proposed by Fang et al. (2015), is implemented within an ABM platform. In SFM, the behavior of each evacuee is assumed to be controlled by a rational "thinking process". Agents are able to perceive and assess 'thoughts', including desired goals and social and group relationships, and respond to those factors through locomotion. These goals may comprise the evacuee's need to exit, avoid collision with walls and other agents, move toward related agents, keep private spacing, and respond to social relationships, which describe the interaction among people at the social level. All these factors are evaluated quantitatively as a series of scalar quantities and processed by the Scalar Field Method.

The scalar quantities, termed virtual potential energies (VPEs), are computed as a function of distance to other agents or objects in the environment, in a manner similar to what occurs for potential energy of a charged particle in an electromagnetic field. Because all the computations involve scalar quantities (hence the name), the VPEs from various sources can be directly added together to form a comprehensive field around the agent that signifies the additive or subtractive effects of issues of importance to the agent. The analogy to electromagnetic fields implies that the desire to take action will be guided by the intent of minimizing the VPE. The premise of the model is that the lower the value of VPE, the greater will be the intent to take action, and vice versa. The SFM has some conceptual similarities to a model proposed by Georgoudas et al. (2010), albeit that model is based on cellular automata.

Each agent in the Fang et al. (2015) model is autonomous and processes a sequence of algorithmic steps akin to "decision-making": observe and update perception; refresh sampling points for VPE computation; compute an evacuation route; estimate others' movements; calculate VPEs to reach a locomotion decision; and execute the decision. In the second-to-last step, an agent's locomotion is decomposed into translation and rotation. The agent needs to first consider whether to rotate or not and afterwards translate when an orientation decision is made. Both rotation and translation decisions are based on VPEs computations. While full details of SFM and its implementation can be found in Fang et al. (2015), the VPE governing equations are shown here for the sake of completeness:

$$E_1 = c_1(d_1 + D_{1a} - D_{1e}\cos(\Delta\theta_1)) \tag{1}$$

$$E_2 = \begin{cases} c_2\left(\frac{1}{(d_2 - R_A - R_{T,other})} - \frac{1}{D_{20}} + E_{2,counter}\right), & d_2 - 2R_A < D_{20} \\ 0, & d_2 - 2R_A \geqslant D_{20} \end{cases} \tag{2}$$

$$E_3 = \begin{cases} c_3\left(\frac{1}{(d_3 - R_T - R_S)} - \frac{1}{D_{30}}\right), & d_3 - R_T - R_S < D_{30} \\ 0, & d_3 - R_T - R_S \geqslant D_{30} \end{cases} \tag{3}$$

where E_1, E_2 and E_3 are the VPEs of the goals to exit a building, preserve private space, not collide with other agents and with walls; d_1, d_2 and d_3 are the distances between agent and exit, other agent and wall, respectively. $\Delta\theta_1$ in Eq. (1) is the absolute value of the angle difference between the forward facing orientation of an agent and the direction pointing to the target object. c_1, c_2 and c_3 are strength constants assigned to be 200, 5, 1. D_{20} and D_{30} are influence distances in Eqs. (2) and (3), respectively. Agents and other entities within the influence zone can interact together in a VPE sense; otherwise they are unable to influence one another. D_{1a} is 10 m, and D_{1e} is 0.5 m that associated with the orientation of an agent; R_A is the radius of an agent in the direction of interest. To simplify