Environmental Effect on Egress Simulation

Samuel Rodriguez[1], Andrew Giese[1], Nancy M. Amato[1], Saied Zarrinmehr[2], Firas Al-Douri[3], and Mark J. Clayton[2] *

[1] Parasol Lab, Dept. of Computer Science and Engineering, Texas A&M University
[2] Dept. of Architecture, College of Architecture, Texas A&M University
[3] University of Nevada, Las Vegas (UNLV), School of Architecture
sor8786@tamu.edu,awg4619@tamu.edu,amato@tamu.edu,zarrinmehr@neo.tamu.edu,
firas.al-douri@unlv.edu,mclayton@arch.tamu.edu

Abstract. Evacuation and egress simulations can be a useful tool for studying the effect of design decisions on the flow of agent movement. This type of simulation can be used to determine before hand the effect of design decisions and enable exploration of potential improvements. In this work, we study at how agent egress is affected by the environment in real world and large scale virtual environments and investigate metrics to analyze the flow. Our work differs from many evacuation systems in that we support grouping restrictions between agents (e.g., families or other social groups traveling together), and model scenarios with multiple modes of transportation with physically realistic dynamics (e.g., individuals walk from a building to their own cars and leave only when all people in the group arrive).

1 Introduction

Serious injury and even death can occur during entry, occupancy and evacuation of a building. Incidents in which people are seriously injured or killed due to crushing or trampling are not restricted to emergencies such as fire, crowd violence, or even simple exuberance of some members of a crowd. Indeed, injuries can happen under conditions that might, in every other respect, appear to be normal even to people in close proximity to those hurt in the incident [12]. Such events can occur, and have occurred at sports events and music concerts.

Such problems are influenced by design features, some of which are dictated by standards, safety codes and regulations mainly in relation to means of egress and, to a lesser extent, movement safety. Empirical studies of crowd movement suggest a more cost-effective, performance-oriented approach to selecting and designing egress location, width, and configuration [12]. To examine how egress location, width and configuration affect the way people behave and move around those egresses, agent based models can be used to realistically model agent behavior and interaction [23]. Those models are used to help explore the behaviors of agents as they plan evacuation routes in the environment to areas that are

* This research supported in part by NSF awards CRI-0551685, CCF-0833199, CCF-0830753, IIS-096053, IIS-0917266 by THECB NHARP award 000512-0097-2009, by Chevron, IBM, Intel, Oracle/Sun and by Award KUS-C1-016-04, made by King Abdullah University of Science and Technology (KAUST).

considered safe. This includes giving the agents adequate representation of potentially complex environments and having them perform behaviors in these environments. While there has been a great deal of work in evacuation planning when agents are undergoing some amount of *panic* [9, 13], there has been less focus on more general egress planning. For example, scenarios seen in everyday life in which agents, with social grouping restrictions, plan routes to a particular vehicle (e.g., their car or a bus) and then continue to exit, for example, from a parking lot.

In this work, we utilize an agent-based system to simulate egress in a scenario with pedestrians and a scenario with groups of agents leaving one area of an environment, such as a building, moving to a vehicle, and then exiting from a parking lot. An overall goal of our work is to provide a training tool to enable a designer to see potential bottlenecks in a design before construction. The software may also allow someone to analyze an evacuation in an existing environment to see how and where to best place emergency/directing personnel.

The main contributions of this work include:

- An integrated roadmap-based and agent-based approach that can represent both broad and subtle aspects of human motion in pedestrian or automotive modes, and transitions between them.
- Demonstrating the approach can be used to analyze the effect of architectural elements on agent egress.
- Agent groups for scenario building and enhancing overall approach.
- Highlighting the need for sophisticated local and dynamic planning strategies for groups of agents.

Our overall approach can be used to handle many of the evacuation scenarios that others have have studied. However, we extend the scope of the problem by considering the fact that in many egress scenarios there is a vehicle involved which dictates additional constraints on the system. Effective planning of the motion for both agents evacuating an environment and vehicles exiting a parking lot are of critical importance to our work. We show the importance of randomized local planning in handling complex environments and also planning in dynamic areas. The grouping we support allows us to handle social grouping of agents such as people traveling together to an event and who only leave after they have all re-grouped, perhaps at a vehicle or mass transit station. We show the usage of our egress planning simulation as a tool to study the effect of different design decisions on agent movement.

2 Related Work

A number of issues are relevant when simulating agent egress in virtual environments. There have also been many systems that have been proposed. Here we describe a few of the most relevant issues including considering different modes of transportation, force-based models, the complexity of environments, collision avoidance and evaluation of motion. As described below, there has been a lot of work in virtual environments, some focused on evacuation and planning and motion in dynamic environments. Our work will is informed by and incorporates aspects of these approaches into a full system for general egress planning, considering a broader range of the whole problem.

(a) Parking Lot 1 (b) Parking Lot 2 (c) Actual parking lot

Fig. 1. Example environments with parking lots. (a) Parking lot 1 configuration at a snapshot of the egress process and (b) Parking lot 2 configuration at initialization. (c) Parking lot modeled after an actual parking lot on our campus.

Multiple Modes of Transportation. The complex relationship between different modes of transportation is an issue in the full scale egress scenario. These interactions can cause obstructions, waiting and even harm if not fully explored. In [3], vehicle and pedestrian interaction is explored at an airport parking lot. In this approach, pedestrians can block vehicles and a single pedestrian initiates movement of a vehicle. Vehicles in the cellular automata framework have simplified dynamics given the discretized space. The movement is restricted in the direction of the grid cell and each cell can only hold one vehicle at a time. They can capture elements of microscopic simulations including following, lane changes, protected turns and unprotected turns. Another approach is presented that describes the need to consider the vehicle aspect of actual evacuations where vehicle and pedestrian flows are considered together [24]. They claim that in an evacuation of an area, pedestrians can vastly influence the overall evacuation and even prevent planned direction from optimizing movement. The underlying model is graph-based with independent network representations for the vehicles and pedestrians. The combination of the networks is used to analyze conflicts which usually occur at intersections or crossing areas.

Evacuation and Navigation. A number of approaches for pedestrian only navigation have been studied. In a survey, focused on virtual crowds [14], work is described about many approaches that have been proposed for crowd simulation such as the types of models that have been developed with an in-depth look at a few different models. One approach attempted to simulate agent panic when evacuating simple environments [9]. An approach to find the optimal evacuation time in simple 2D environments is described in [17] where the occupants have n possible exits and use an evacuation function to select routes. The idea of different levels of agent knowledge and planning ability is considered in [15]. This is in part due to psychology studies which show that building occupants usually decide to use familiar exits, such as where they entered the building. In [13], a system is developed for simulating the local motion and global way finding behaviors of crowds moving in a natural manner within dynamically changing virtual environments. They are able to simulate patient and impatient agents and pushing between agents. Improvements on previous work, [9], were made by considering factors that reduce shaking and vibration caused by applying social forces in densely crowded areas. They also consider the problem of avoiding bottlenecks to pick better routes.

Force-based models have been developed where forces on agent influence the overall movement of the agents. These forces are often defined by the local environmental information including the nearby agents, walls, desire to align or avoid collision with neighbors [18, 9, 13].

Grouping. Physical factors are considered in [22], but the ability and need to include social grouping is also described. There are also known evacuation scenarios where agents have vastly different traveling speeds which includes people with disabilities [4] who may require evacuation in groups. Another work that describes the need to consider grouping in evacuation is [10], where depending on the population type, agents may be either individuals or be considered familial groups which may contain small children.

Complex Environments. There has been some work focused on more complex environments which are encountered in the real world. Pedestrians evacuating a large stadium are shown in [5]. These agents operate on a simplified network graph of the stadium and generally follow the agent ahead of them given the constrained environment. Evacuation in high-rise buildings is shown in [16] using a cellular automata approach. The environment is discretized into grid-cells of free space or blocked space and agents select evacuation routes based on finding a path through unoccupied cells. Limitations of this approach are factors such as grid size, ignoring fatigue factors, route selection through the underlying grid, uneven usage of stairwells, and their difficulty in simulating stairwells using this approach. While these approaches are very interesting given the complexity of the environment, the abstraction of the problem may lose too much information about the environment.

Collision Avoidance. There have been a number of approaches proposed where nearby agents coordinate with one another. Some approaches consider other nearby agents as velocity obstacles [7, 2]. This allows the agents to plan valid paths in very constrained environments while avoiding collisions with nearby pedestrian agents. In a similar approach [6], an optimization function that all agents share and use when generating trajectories allow them to attempt to minimize the amount of energy used by the agents and even avoid congested areas. A modular steering framework is proposed in [21] where a number of steering algorithms are combined which include simple forces, reactive steering, space-time predictions, space-time planning, and fully planned paths. The space-time predictions and planned motion allow the agents to overcome deadlocks with local agent interactions. A planner for coordinating between multiple vehicles is presented in [1]. While considering communication, the planner also avoids collision between neighboring vehicles and obstacles.

Evaluating Motion. Many of these systems have needed custom and thorough evaluation of the agent movement. The resulting evacuation movement is evaluated in [9] by looking at properties such as leaving time, number of injuries, flow and door usage. In [20], the problem of objectively comparing steering algorithms is investigated. They propose a set of test cases that can be used inluding agent-to-agent cases and between groups of agents. A number of metrics are also described and scoring methods that can be used are presented. The idea of evaluating steering algorithms is extended in [11] where the authors attempt to characterize the entire scenario space and extend the evaluation criteria to determine the coverage and the quality of a steering methods.

3 Egress Simulation: Agents, Motion and Behavior

In this section we describe each component of our multi-agent system and how we integrate planning with the behaviors we are simulating. Key components of our approach include the agents, system initialization, restrictions between agents, the behaviors each agent is executing and the forces that the agents apply throughout the simulation.

3.1 Agents

Agents in our system represent an individual or entity with its own set of properties. Examples of agents that we model include an agent attempting to evacuate, directors (individuals or other objects) that can guide and cooperate with other agents, and vehicles.

An agent is defined by a number of attributes. Movement properties (velocity and acceleration) dictate the speed at which the agent can move while navigating through the environment. The way forces affect the motion of agents is described in Section 3.2. Environmental knowledge includes the exits and safe areas/destinations that are known to an agent. In our system, agents are given differing levels of environmental knowledge to more accurately represent real-world situations where individuals may not know everything about a building they are in. Environmental mapping is the level at which the environment is mapped and used in navigating through the environment. Our roadmap-based approach allows us to handle complex environments which is essential for actual situations. Restrictions between agents exist in order to allow certain evacuating agents to be grouped with a vehicle and vice versa.

Pedestrians: Pedestrian agents represent individuals in the environment with human like restrictions on their motion and environmental knowledge. These agents have the ability to walk or run in the environment. In the scenario we are studying the agents plan their final route to either a destination that is known to them or a vehicle to which they are assigned. Many evacuation systems focus on pedestrian motion.

Vehicles: The vehicle agents in our framework are independent agents in that they plan on their own routes, however they could be initialized with information from a leader agent that is associated with the vehicle. Their motion is restricted by car-like maneuvers so their range of motion is less dynamic than pedestrians. Like pedestrians, these agents are equipped with a set of destinations and exits, which are typically different than those for pedestrians. Vehicles with pedestrian agents associated with them have to wait until all agents have reached them.

Guidance Agents: In our previous work we have explored the idea of director agents placed in the environment to influence evacuation [19]. These director agents would alert evacuating agents about safe areas, the unavailability of exits or the existence of a dangerous area in the environment. The guidance agents we focus on in this work are part of the environmental structure that could influence the motion of agents. Examples of these agents include immovable pillars in the environment or moveable objects placed by other directors to funnel agents through certain parts of the environment. These are components that a designer or architect may want to add to an actual structure.

3.2 Agent Motion

The motion of the agents is determined by the forces acting on the agent at each time step. We consider a number of forces that can affect the movement of agents. The forces acting on an agent affect the velocity, with the velocity in turn affecting the agent's position and orientation.

A goal-based force allows an agent to move along a global path that has been computed. In this force rule, the agent will attempt to push itself toward the next subgoal along a path. The force that is generated is simply in the direction given by the agent's current location to the subgoal along the path. The basic goal-based force rule does not account for restrictions on the agent movement.

We also employ a simple *avoidance* force rule. This force rule attempts to generate a force away from agents that have been observed to be nearby (as in one of the avoidance force described in [18]). The agents can have this avoidance force applied to any set of agents and all the forces can be composed given the defined force rules. As an example, an evacuating agent can have a goal-based force rule which will push an agent along its path, an avoidance force focused on other evacuating agents in order to avoid agents navigating near it in a building and another avoidance force away from vehicles.

Our vehicle force rule is very similar to the standard goal-based force rule but with added restrictions. One restriction is stopping if another agent is within some predefined distance and angle to it's heading direction. Another is restricting the allowable force that can be applied to vehicles so that sharp changes of orientation do not occur. Another restriction is having the vehicle reverse if necessary to allow for more space to reach a subgoal along the global path. Our current stopping conditions only consider the region ahead of a vehicle when determining when to stop. This can result in some agents moving near one another, in a similar direction, to overlap before a collision is identified. A more robust stopping criteria should be used to ensure overlap does not exist.

3.3 Egress Behavior

We explored the basic egress behavior in our prior work [19] which defined the process that the evacuating agents use to find a route through the environment. The additions in this work allow for agents to be associated with vehicles and have vehicles wait for the agents associated with them, Alg. 1. The process of finding a route is based on the exits and safe areas/destinations that are known to agent a_i. An agent evaluates routes through the environment from it's current location to a destination given the known exits and destinations and selects the route to the destination with the lowest weight. We do not require all agents to have the same or complete information. It is also dependent on whether restrictions are given to the agent, having either a target vehicle assigned to it, or having a group of agents associated with the vehicle agent. In this way, the same behavior is applicable to both evacuating agents and vehicles with the main difference being the destinations and exits that are considered during the route finding process. For vehicle agents, the global route obtained is used as the global plan and the local plans are generated to be biased along the global plan.

Problem Initialization. The scenarios that we are simulating require some detailed initial placement of agents. This includes placing individual agents at

Algorithm 1 Route Selection for Agent

Input: Agent a_i, known exits E, known destinations/safe areas SA

if a_i.hasAssociatedAgents() **then**
    if ! a_i.allAssociatedReached() **then**
        return
    end if
end if
for all $e \in E$ **do**
    $route$ = generateRouteToDestination(e, SA)
    $score$ = evaluateRoute($route$)
    if $score$ of $route$ is best **then**
        Save $route, score$
    end if
end for

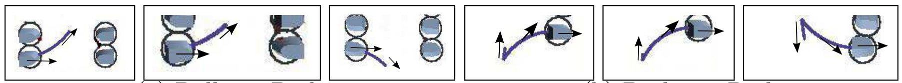
pre-defined areas in an environments. For vehicle agents in a parking lot, the vehicle agents need to be placed in a way that accurately represents parking lots, Figure 1, which includes placement and orientation of the agents.

The grouping restrictions that have been mentioned allow our simulation framework to handle the fuller egress scenario that happens much more frequently in everyday life. The grouping restrictions that are exhibited in the simulation for this scenario is associating a set of agents with a vehicle. These associations are considered in the behavior which allows us to use the same behavior for different sets of agents given their associations. Additionally, agents do not need to be grouped with other agents so that they may act completely independently.

3.4 Egress Mapping and Planning Requirements

Global Planning: Mapping the Space for Individuals. For evacuating agents that need a global path, we use a roadmap-based approach. This roadmap encodes valid transitions from one area of the environment to another. The roadmap allows us to quickly and efficiently represent complex spaces with a representative map of an environment and allows us to handle more complex environments that many other systems. For example, we used roadmaps in our prior work to explore pedestrian evacuation of complex structures [19]. During an evacuation scenario, agents will plan routes using the roadmap towards a destination. These paths are used as a guide for the agents to follow.

Local Planning for Vehicles with Dynamics. Vehicles planning out of a parking spot have much more restricted motion and we consider only a subset of all potential motion to plan for agents to be able to follow the global path. These motions include simply pulling out of a parking spot, shown in Figure 2, or backing out of a spot, reversing away from a subgoal along the global path and then moving towards the subgoal. These motions are all made given the vehicles pre-defined dynamics. These local planned paths are considered successful if they do not collide with neighboring agents, the environment and result in the vehicle facing in the direction of the subgoal along the global path.



(a) Pull-out Paths (b) Back-out Paths

Fig. 2. Examples of locally planned paths allowing agents to either pullout of a parking spot (a) or back out (b). Vehicle orientation shown along the path.

Integrating Planned Motion with Reactive Motion for Vehicles. When a vehicle agent has its associated agents arrive and is ready to start following its global route, the first step is to plan a local path to a subgoal along the global path. Once a valid local path has been generated, the vehicle starts following the planned local path. While other nearby vehicles are following a locally planned path we do not allow other vehicles to plan a local path. Once a vehicle is done following a local path, the vehicle switches to the vehicle-like force rule following the global path at the subgoal that was planned to. One drawback of our current implementation is that the local path generated considers all nearby agents to be not moving at the time the plan is generated. This may result in some overlap when a vehicle is following a locally planned path and another vehicle is following a global path but cannot stop in time to avoid collision.

4 Egress Scenarios and Metrics

Our system has been applied to several scenarios to explore the consequences of alternative architectural designs on egress. The first scenario is a building modeled from an actual building on the campus of Texas A&M University. Four hundred agents are placed throughout the first five floors and leave through a single available exit. The single exit is used so we can test variations at that one exit and isolate the differences that occur. The adaptation of the environment is along two exit ramps where Ramp 1 is a preliminary ramp and the second ramp leads directly out of the building. The variations are shown in Figure 3 where we vary the number of exits and we highlight how architectural components might affect egress given different environmental placements of immovable pillars near exits. We also place a crowd of 25 agents near the 6 pillars that act as obstacles that the agents leaving the scene can push through.

The second scenario is shown in Figure 1. It consists of a multi-level structure containing 200 pedestrian agents and a parking lot consisting of 40 vehicles. Agents are grouped into subgroups of 3 to 5 agents per vehicle. Agents with a grouping restriction with a vehicle plan their egress route to the vehicle and the remaining agents plan an egress route to a safe area on the boundary of the environment in Figure 1. The pedestrian agents are placed on the lower level so we can focus on the impact of the two versions of the parking lot shown in Figure 1(a) and (b). In (a), vehicles are initially parked in long rows with barriers used to guide the motion of the vehicles and in (b), vehicles are parked in four smaller lots, again with barriers present to guide the motion.

A common metric used to analyze egress is evacuation time [9, 20]. This represents the time at which all agents have left the area being evacuated. In order to capture the main differences in the design scenario, we utilize an evacuation time

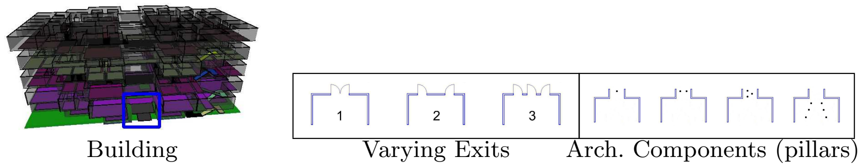


Fig. 3. Examples of environmental changes we study in our scenario. Pillar locations and door placements are shown along with building (exit highlighted).

at which a pre-defined percentage of the population has left the designated area (in the experiments this is set to 96 percent). This accounts for agents initialized with slower speeds and initial placements at extremes of the environment. In the building only case, the evacuation area is the bounding box around the building at the ground plane and for the parking lot scenarios, the evacuation area is the area enclosing the lots and extending to the road leading to the safe area.

Another metric we report for the pedestrian case is the number of significant collisions given an overlap value [9, 20]. Our overlap is determined by the distance between nearby agents and their body radii. When the overlap reaches a predetermined value it is reported and resolved. The larger the number of collisions given the overlap value, the more likely it is that congestion was occurring. It is also important to note that our collision resolution allows for overlap between agents, which includes between pedestrians and vehicles and the collision is not resolved until the overlap requirement is met.

For pedestrian only egress, we report overall average speed at a surface. We have divided the environment into two portions at the exit location (Ramp 1 and 2). At each time step, the overall speed of the agents moving over each surface is tracked. Over the course of the entire simulation, the overall speed for all agents on the surface is accumulated and reported. Given that this value is accumulated over the full simulation, small differences in the average speed can mean big differences in the speed agents actually travel when congestion occurs.

5 Simulation Results

In this section, we show how our system is sensitive to changes in the environment and applicable to complex environments. We show simulation results for pedestrians leaving a building structure and full scale egress of a building and parking lots environments. Overall, our system is very tunable and can be tuned to match values found from real world observations. Videos showing additional results can be found on our webpage:
http://parasol.tamu.edu/groups/amatogroup/research/flock/.

5.1 Varying Design of Building Environment

The first environment where we show environmental effects on egress is in the office building shown in Figure 3 and described in Section 4. Agents are allowed to travel 2-3 units/second and have goal-based force rules, and avoidance force rules between other evacuating agents, pillars in the environment and the crowd,

Scenario	Egress Time	CollisionCount Overlap=0.2	Overlap=0.3	Ramp$N$ Overall AvgSpeed	Ramp1 Overall AvgSpeed
(a) 1exit	7,153	24,581	11,499	2.09	2.05
(b) 1exit (shifted)	7,600	40,546	14,735	2.07	2.04
(c) 2exit	7,123	21,705	9,207	2.10	2.05
(d) 2exit (shifted)	7,224	23,187	9,052	2.10	2.06
(e) 3exit	7,102	23,570	9,383	2.11	2.05
(f) 3exit (shifted)	7,314	22,064	9,639	2.10	2.04
(g) 1exit 1pillar	7,286	27,582	13,019	2.04	2.04
(h) 1exit 2pillar	7,381	31,340	15,325	2.03	2.04
(i) 1exit 3pillar (aligned)	7,636	37,656	16,892	2.04	2.02
(j) 1exit 3pillar (staggered)	7,544	43,652	21,406	2.05	2.01
(k) 1exit 3pillar (EQ1)	7,731	48,058	23,643	2.07	2.02
(l) 1exit 6pillar	7,219	25,726	12,314	2.07	2.02
(m) 1exit 6pillar with crowd	8,900	134,507	77,989	2.05	2.02

Table 1. Results for 8 different environmental scenarios showing evacuation time, significant collisions (depending on overlap value) and overall average speed.

if one exists. In Table 1, results show overall average egress time, significant collisions given an allowable distance proportion, and average speed through the simulations at each ramp.

In the case of varying the number of exits, we can show that increasing the number of exits does reduce, although slightly, the evacuation time but can greatly reduce the number of significant collisions and improve overall speed over the second ramp. We also show an example where the exit placements are shifted to align with the edge of the previous ramp. In all cases, the shift increases egress time which is likely due to the increased congestion of agents moving towards the exit at a corner.

Varying pillars in the environment, given the 1-3 pillar placements, a slowdown in egress can be seen and actually increases as the number of pillars increase. This can be due to the placement and the proximity to the actual exit on Ramp 2. This can be seen in evacuation time and number of significant collisions. When comparing three different placements in the 3 pillar example, it can be seen that our system is sensitive to the configurations of the pillars. The staggered placement leads to a better egress time than the aligned pillars or those forming an equilateral triangle which supports the idea of pillar placement affecting flow [9, 8].

When adding 6 pillars to Ramp 1, evacuation time, significant collisions and overall speed are not greatly affected. We also show how these values are affected as a crowd is added around what might be considered the interesting structural components, in this case, the pillars. As expected not only egress time increases but the number of significant collisions is also greatly increasing.

5.2 Larger Scale Egress of Building and Parking Lot

In the parking lot example, the average egress time of parking lot 1 is 9,664 time steps which is much lower than in lot 2, with an evacuation time of 11,079. This can be due to a number of factors, such as the pedestrian agents, at times, plan their route to their vehicle through the parking lot and cause more blockage in the case of lot 2. There are also more bottlenecks formed between the enclosures of the parking structures in the case of parking lot 2 versus parking lot 1. This is a fuller scale egress scenario and larger in scope than many evacuation scenarios. We believe this kind of simulation tool can be useful to designers of virtual worlds and tuned to match real world scenes.

We have even been able to simulate a larger scale parking lot scene, shown in Figure 1(c), which is a simulated model of an actual parking lot and building near the building used for the pedestrian examples. Simulation results are presented in our animations. These parking lot scenes capture many aspects of parking lots egress observed in the real world with vehicle agents following one another and allowing some space between vehicles (a parameter that can be tuned), merging at bottlenecks and vehicles stopping to avoid collision with pedestrian or other vehicles.

6 Conclusion

In this work, we consider a complex and complete egress scenario which includes pedestrians, vehicles, guidance agents and environmental effect on agent flow. This work allows us to observe through simulation the effect of a proposed design and identify potential implications of it. This larger scale problem is one that is more frequently seen than panic evacuation and can be of use to building and environment designers in the real and virtual world. The initial experiments suggest that the approach of combining a roadmap that simplifies the scene with simple motion behaviors and more complex egress behaviors can be sensitive to real-world factors in architecture.

References

1. Bekris, K.E., Tsianos, K., Kavraki, L.E.: A decentralized planner that guarantees the safety of communicating vehicles with complex dynamics that replan online. In: Proc. IEEE Int. Conf. Intel. Rob. Syst. (IROS) (2007)
2. van den Berg, J., Guy, S.J., Lin, M., Manocha, D.: Reciprocal n-body collision avoidance. In: Proceedings of Robotics Research: The 14th International Symposium, ISRR. pp. 1–16. Madrid, Spain (2011)
3. Blum, J., Eskandarian, A.: The impact of multi-modal transportation on the evacuation efficiency of building complexes. In: Intelligent Transportation Systems, 2004. Proceedings. The 7th International IEEE Conference on. pp. 702 – 707 (oct 2004)
4. Christensen, K., Sasaki, Y.: Agent-based emergency evacuation simulation with individuals with disabilities in the population. Journal of Artificial Societies and Social Simulation 11(39) (2008)
5. Fang, Z., Li, Q., Li, Q., Han, L.D., Wang, D.: A proposed pedestrian waiting-time model for improving space-time use efficiency in stadium evacuation scenarios. Building and Environment 46, 1774–1784 (September 2011)
6. Guy, S.J., Chhugani, J., Curtis, S., Dubey, P., Lin, M., Manocha, D.: Pledestrians: A least-effort approach to crowd simulation. In: SCA '10: Proceedings of the 2010 ACM SIGGRAPH/Eurographics Symposium on Computer Animation. Eurographics Association, Madrid, Spain (2010)

7. Guy, S.J., Chhugani, J., Kim, C., Satish, N., Lin, M., Manocha, D., Dubey, P.: Clearpath: Highly parallel collision avoidance for multi-agent simulation. In: SCA '09: Proceedings of the 2009 ACM SIGGRAPH/Eurographics Symposium on Computer Animation. pp. 177–187. Eurographics Association (2009)
8. Helbing, D., Buzna, L., Johansson, A., Werner, T.: Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. In: TRANSPORTATION SCIENCE. pp. 1–24 (2005)
9. Helbing, D., Farkas, I., Vicsek, T.: Simulating dynamical features of escape panic. In: NATURE. pp. 487–490 (2000)
10. Johnson, C., Nilsen-Nygaard, L.: Extending the use of evacuation simulators to support counter terrorism. In: International Systems Safety Conference (2008)
11. Kapadia, M., Wang, M., Singh, S., Reinman, G., Faloutsos, P.: Scenario space: characterizing coverage, quality, and failure of steering algorithms. In: Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation. pp. 53–62. SCA '11, ACM, New York, NY, USA (2011), `http://doi.acm.org/10.1145/2019406.2019414`
12. Pauls, J.: The movement of people in buildings and design solutions for means of egress. Fire Technology 20, 27–47 (1984), `http://dx.doi.org/10.1007/BF02390046`
13. Pelechano, N., Allbeck, J., Badler, N.: Controlling individual agents in high-density crowd simulation. In: ACM SIGGRAPH/Eurographics Symposium on Computer Animation (2007)
14. Pelechano, N., Allbeck, J., Badler, N.: Virtual Crowds: Methods, Simulation, and Control. Synthesis Lectures on Computer Graphics and Animation, Morgan & Claypool (2008)
15. Pelechano, N., Badler, N.: Modeling crowd and trained leader behavior during building evacuation. In: IEEE Computer Graphics and Applications. vol. 26, pp. 80–86 (2006)
16. Pelechano, N., Malkawi, A.: Evacuation simulation models: Challenges in modeling high rise building evacuation with cellular automata approaches. Automation in Construction 17, 377–385 (2008)
17. Pursals, S.C., Garzon, F.G.: Optimal building evacuation time considering evacuation routes. European Journal of Operational Research 192, 692–699 (2009)
18. Reynolds, C.W.: Steering behaviors for autonomous characters. In: Game Developers Conference (1999)
19. Rodriguez, S., Amato, N.M.: Utilizing roadmaps in evacuation planning. 24th Intern. Conf. on Computer Animation and Social Agents (CASA), 2011, in Intern. Journal of Virtual Reality pp. 67–73 (2011)
20. Singh, S., Kapadia, M., Faloutsos, P., Reinman, G.: Steerbench: a benchmark suite for evaluating steering behaviors. Comput. Animat. Virtual Worlds 20, 533–548 (Sep 2009)
21. Singh, S., Kapadia, M., Hewlett, B., Reinman, G., Faloutsos, P.: A modular framework for adaptive agent-based steering. In: Symposium on Interactive 3D Graphics and Games. pp. 141–150. I3D '11, ACM, New York, NY, USA (2011), `http://doi.acm.org/10.1145/1944745.1944769`
22. Thompson, P., Marchant, E.: A computer model for the evacuation of large building populations. Fire Safety Journal 24, 131–148 (1995)
23. Torrens, P., Nara, A., Li, X., Zhu, H., Griffin, W., Brown, S.: An extensible simulation environment and movement metrics for testing walking behavior in agent-based models. Computers, Environment and Urban Systems 36(1), 1 – 17 (2012)
24. Zhang, X., Chang, G.: Optimal guidance of pedestrian-vehicle mixed flows in urban evacuation network. In: The 90th annual meeting of the Transportation Research Board (2011)