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Behavior-Based Evacuation Planning*

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***Abstract*— In this work, we present a formulation of an evacuation planning problem that is inspired by motion planning and describe an integrated behavioral agent-based and roadmap-based motion planning approach to solve it. Our formulation allows users to test the effect on evacuation of a number of different environmental factors. One of our main focuses is to provide a mechanism to investigate how the interaction between agents influences the resulting evacuation plans. Specifically, we explore how various types of control provided by a set of directing agents effects the overall evacuation planning strategies of the evacuating agents.**

I. INTRODUCTION

Simulating large numbers of agents performing complex tasks that include interacting with each other and the environment is a difficult problem with applications in robotics, computer graphics and animation. Effective simulations could be used to study and train for emergency or disaster scenarios including civilian crowd control, evacuation of a building and many other important training situations. Behavioral based simulations allow for someone to study the result of agents performing a certain behavior, without having to see this behavior in practice. In the case of evacuation planning, the evacuation of an environment can be studied with different behavioral, environmental and interactive conditions. There has been much work in simulating large numbers of agents performing a basic evacuation strategy. However, there is little that incorporates interaction with control or directing agents which may influence how the evacuating agents perform the evacuation. An important focus of this work is to develop and study such control behaviors, where one group of agents actively tries to control or direct the movement of another group of agents.

The overall goal is to develop an interactive planning and training tool for crowd-based behaviors of large numbers of interacting agents that supports a variety of situations. Realistic simulations for evacuation planning must consider the behaviors of the (groups of) agents and how these entities interact with each other. The behavior of agents and groupings of agents can also add a level of accuracy and detail, which is necessary when studying real world situations. Our focus on the control behaviors allows us to consider some aspects of evacuation scenarios that have so far not been extensively studied.

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While a great deal of work has been done on large-scale multi-agent behavior and evacuation planning, we present some novel techniques to this problem. The main contributions of this work include:

- a motion planning inspired formulation of an Evacuation Planning Problem;
- an integrated behavioral agent-based and roadmap-based motion planning system that supports interaction with control and directing behaviors;
- support for customization based on grouping and environmental factors.

Other approaches to the evacuation planning problem are often restricted to certain aspects of the problem. We define the problem in a general way to include evacuation behaviors that can be used, area types that should be considered, grouping restrictions that may exist and interaction that may occur. One set of behaviors that we focus on, controlling behaviors, require cooperation between the directing agents and the agents that are cooperating. Our behavior framework is very dynamic and includes having behaviors general enough to be applicable to a single agent or a group of agents. This will enable the group of agents performing the behavior to work cooperatively and share goals from the behavior. Our group hierarchy, which organizes the agents and subgroups, has been extended such that behaviors can be applied at any point in time and to groups at any level of the hierarchy. This can help in achieving cooperation and in reducing computation, where groups at a lower level of the hierarchy can benefit from computation done at the higher levels and behaviors can be applied periodically.

The system we describe is tunable so different environmental and behavioral conditions can be tested. We expect that by looking at this problem from a behavioral, evacuation planning aspect, it will allow us to further explore cooperative and complex behaviors.

II. RELATED WORK

A. Roadmap-Based Multi-Agent Behaviors

In [3], [2], [1], the benefits of integrating roadmap-based path planning techniques with flocking techniques were explored. The global information provided by the rule–based roadmaps improved the behavior of autonomous characters, and enabled more sophisticated group behavior than are possible using traditional (local) flocking methods [17].

One key feature of integrating roadmaps with basic group behavior is that the roadmap provides a convenient abstract representation of global information in complex environments. Adaptive roadmaps (e.g., modifying node and edge weights) also enable communication between agents. Associating rules with roadmap nodes and edges enables local customization of behaviors.

The approach we use also utilizes a roadmap, encoding representative feasible paths in the environment. While noting that our techniques could use any abstract representation of the environment, our current implementation is based on the probabilistic roadmap method (PRM) [10]. In this way, a roadmap is created which approximates the connectivity of the free space and can be queried to obtain valid paths.

We have developed some initial roadmap-based controlling behaviors where one group of agents actively try to direct another group of agents. In [12], [13], we investigate shepherding behaviors in which the shepherding agents guide or control members of a flock which react to the movement of the shepherds. We explored advanced techniques for the shepherds to effectively control a flock.

B. Evacuation Planning

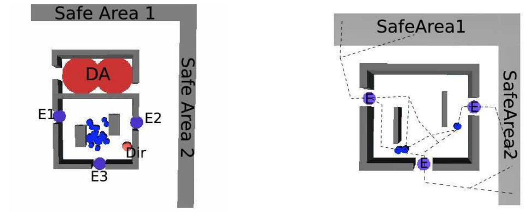
There has been much work addressing different aspects of the evacuation problem. We first give an overview of some interesting work in this area. A survey of the main approaches that have been attempted is presented in [18]. Four approaches were described: flow-based, cellular automata, agent-based and activity-based models. The focus of our work and the related work presented here is on agent-based models since this allows us to have varying agent capabilities and enables complex interactions.

An early work in agent-based evacuation is described in [20]. The goal of this system was to be able to handle thousands of individuals escaping in large, geometrically complex environments. The environments were discretized into grid cells, assigned weights (based on if a grid cell is a solid object, open space or a final destination) and maximum travel distances were computed. This work presented some interesting results but focused mainly on individual agents.

The way individual characteristics impact evacuation efficiency is studied in [4]. This work is based on the social forces model developed in [7], [8] but includes other agent characteristics such as dependence level, altruism and the desired speed of agents. The impact of the individualities in the resulting average flow of people is done when varying the characteristics. They claim that some settings of these parameters can simulate trained people. This is one of the few works that describes the importance of grouping, although their usage of grouping is not described.

The idea of different levels of agent knowledge and planning ability is considered in [16]. This is in part due to psychology studies which show that building occupants usually decide to use familiar exits, sometimes ignoring exits not normally used for circulation. Different agent types are considered including trained leaders, untrained leaders and followers. Communication is considered to share locations of hazards and portions of the building that have already been explored. One interesting result they are able to find is the optimal number of leader agents. They also observed differences in evacuation when changing the population type.

In [15] a system, HiDAC, is developed for simulating the local motion and global way finding behaviors of crowds moving in a natural manner. They make many improvements on previous work([7], [8]) by considering factors that reduce shaking and vibration caused by applying social forces in densely crowded areas and instead use stopping conditions. Some other interesting factors of this work include avoiding fallen agents, obstacle avoidance, considering a region of influence (ahead of agents), an organizing behavior and pushing between agents. They also consider the problem of avoiding bottlenecks to pick better routes.



(a) Labeled Example (b) Example Routes

Fig. 1. In (a) an example environment is shown where an evacuation planning problem can be studied. Evacuation agents, shown in blue, are clustered in the lower room. Exits are labeled E# along walls of the rooms. The safe areas are labeled along the boundaries. A dangerous area is labeled DA in the second room. A directing agent is placed in the bottom, right of the lower room. In (b) potential evacuation routes to safe areas are shown.

One of the main benefits of agent-based systems is that heterogeneous agent populations can be created to study evacuation. This was done varying the characteristics of agents [4], varying agent knowledge and training information [16], including patient and impatient agents [15]. There are also known evacuation scenarios where agents have vastly different traveling speeds which includes people with disabilities [5] and may require evacuation in groups. The need to consider grouping in evacuation is described in [9], where depending on the population type, agents may be part of familial groups which may contain small children.

Many different approaches have been proposed to handle specialized environments. Pedestrians moving through Penn Station were studied in [19]. The evacuation of different areas have been considered including in underground malls [6], in Zurich [11], a passenger ship [9] and at Linz Central Station [14] to help in the design and permit application process. This all points to the need for a flexible system that can be used in a variety of situations and be able to simulate a number of different conditions. The system required will also need the ability to easily vary the agent population types, abilities and group structure requirements.

III. Problem Definition

In this paper we propose a generalized approach for studying the evacuation planning problem. We first describe the basic problem and then some extensions.

The basic problem can be stated as follows: Given an environment composed of polygonal obstacles and N agents, $A = \{a_1, a_2, ..., a_N\}$, in an enclosed area ($EA$), find a valid evacuation plan for each $a_i \in A$ satisfying given constraints. These constraints (some shown in Figure 1) deal with areas that should be avoided and areas that evacuation routes can and should pass through.

This most basic form of the problem involves each agent finding a path through the environment from their starting location through an available exit and finally, to a safe area.

This is similar to the motion planning problem where the objective is to find a path from a start to goal configuration that avoids obstacles. The evacuation route that an agent selects when only considering potential exits may be based solely on distance. A safe area is a region, outside of EA, that is used when generating a final goal location.

Dangerous areas may exist in the environment that the agents should avoid if possible. When evaluating paths, while considering these areas, a potential route that passes through a known dangerous area should be considered less desirable than a path that is clear of the area. In the case that dangerous areas are unavoidable, then routes that minimize the intersection with these areas should be most desirable.

In this form of the problem, we assume the agents have shared knowledge. This includes their knowledge of the environment, areas present and a shared roadmap, which the agents may use when generating evacuation routes.

Dynamic areas. In actual evacuation scenarios these areas exist and should be considered in a general framework. These are areas that can appear at any time or whose shape can alter as the scenario progresses. One example of this area is a congestion that may occur as too many agents are present. Another example is a toxic spill, an area which may expand. While we do not consider these areas in this paper, it is something we are interested in studying.

Grouping. During an evacuation agents may be grouped with other agents. This is a key constraint often overlooked in many approaches. This constraint requires that agents that are grouped stay within some predefined range of one another while moving through the environment. This can represent a familial tie or assistance provided between agents.

Direction. Another key aspect that is often overlooked in many evacuation planning approaches is the ability for one group of agents to direct the evacuating agents. The directing agents can represent a number of direction types including barriers or agents that can provide local or global information. Local information can consist of a nearby exit or safe area to avoid while global information can be many areas to avoid.

Heterogeneous Agent Knowledge. The agent's knowledge of each of these areas and their communication with other agents will effect the evacuation routes that are generated. An agent can compute an evacuation route with it's current knowledge but this route should be updated when the agent's knowledge changes. The knowledge an agent has about the environment can be either predefined, observed or communicated. This can also include having different knowledge about how to navigate through an environment, which can be represented by varying roadmap quality.

These different aspects are key to be able to create a general evacuation planning framework. In the following we will describe in more detail the approaches we have attempted and think should be supported.

IV. Overview of Approach

We utilize an agent-based, distributed planning approach as we study the evacuation problem. This allows us to easily study different sets of agents and allows us to easily vary agent's behaviors and capabilities.

Agents and Behaviors. Some of the capabilities that can vary between agents include a view radius and angle or maximum velocity and acceleration. The roadmap that an agent is equipped with is also a capability since the connectivity and mapping of the environment can play a role in how the agent performs.

The behavior that the agent is equipped with will determine how the agent reacts throughout the simulation. These behaviors determine the actions that the agent or groups of agents take. The behaviors we develop need to be dynamic enough so that they can be applied to an agent at any point and the agent will then start performing that behavior. This can be a difficult task since we do not guarantee a frequency with which a behavior will be applied. This is different than in many of our previous behaviors where at each time step each agent would have their behavior rule applied.

The behaviors we develop need to be general enough to be applicable to a single agent or group of agents. We show results for agents performing an evacuation behavior with grouping restrictions. The behavior created is the same for a group as for a single agent with the addition of some logic that ensures the group remains in tact.

Group Structure. An important distinction that should be mentioned at this point is that we use a general group structure to implement both groups of agents and single agents. A single agent is simply a group with no subgroups. This makes creating our framework more general, especially when creating behaviors.

In many situations it is important to have agents moving through the environment with grouping restrictions, for example having to remain within some predefined distance of other agents. This is also important in that using grouping can help with coordination. As an example, a group that is performing an evacuation behavior need only have the main grouping of agents perform that behavior. Agents at lower levels in the group hierarchy then only need to follow along the group path, an outline is given in Algorithm 2.

Utilizing Roadmaps. One of the most basic ways to use a roadmap is to extract valid paths through the roadmap. Finding a path using a roadmap consists of first connecting the start and goal positions to nodes in the roadmap. Once the connecting nodes have been found, finding a path through the roadmap is a simple graph search. This allows us to easily construct routes between intermediate way points.

V. Areas and Hazards

We consider a number of different area types in creating our framework. This is to allow it to be more general and handle a wide range of scenarios. A general area definition is used to represent to a number of geometric regions. For example, in 2D this can be above or below a certain value along an axis or one or more point–radius pairs. More advanced area types could include polygonal regions or ones defined by a roadmap, which can include a collection of nodes and the transitions between them.

A. Area Types

In our simulation, an exit is an area used when performing evacuation. Agents use this area as a subgoal to a safe location. We often defined exits as a set of point–radius pairs.

Safe areas are used in our simulations as goal areas for the agents to reach. These areas often define a wider range of space, for example near the boundary of the environment but can also be represented as point areas (as with exits). Example exits and safe areas can be seen in Fig. 1.

B. Hazardous Areas and Changing Areas

A hazardous area is another important thing to be able to simulate. We allow these kinds of areas to be represented by any area type. Although we only show examples with static hazardous areas, in a complete framework this kind of area could happen at any point and time in the environment. It could also spread and expand as the simulation progresses.

VI. Safe Planning

Agents planning a path to a safe location have to take into account different environmental aspects. This includes considering available safe exits, potential dangerous regions, locations that are considered safe and any other subgoals that must be reached along an evacuation route. The roadmap is well suited for finding these kinds of paths. Using path evaluation and roadmap re-weighting, paths can be found that satisfy constraints that are known to an agent.

A. Route Selection

A roadmap can be used to extract a safe path through the environment. A path can be extracted from the roadmap with the lowest weight (where weights can represent anything from distance to hazard levels).

Selecting a safe route through the environment, using the roadmap, can be done when considering exits and safe areas that are known. An overview of this process is shown in Algorithm 1. An illustration of this process in a simple environment is shown in Figure 1(b).

Algorithm 1 Route Selection

```
Input: Agent s_i, known exits E, known safe areas SA
for all e ∈ E do
    if s.hasMarkedExitAsAvoid(e) then
        continue
    end if
    P1 = findPath( s_i.getPos(), e.posInArea() )
    nSA = nearestAvailableSafeArea( e, s_i )
    P2 = findPath( e.posInArea(), nSA.posInArea() )
    P3 = P1 + P2
    score = evaluateExitRoute( P3 )
    if score of P3 is best then
        Save P3, score
    end if
end for
```

B. Evacuation Behavior

An agent performing an evacuation behavior uses the safe planning, route selection techniques. Part of the evacuation behavior involves updating an agents' information about known dangerous areas. An agent updates it's own information when discovering new areas, either by observation or communication with other agents. The paths that will be selected are by the lowest edge weight. In this way, areas can be avoided by assigning higher edge weights to areas that have been marked as areas to avoid. This will prevent routes being selected that pass through these areas.

Algorithm 2 Agent Path: using Group Info

```
Input: Agent s_i and associated group G_i
# Goal: find next goal based on group position & velocity
Dir = G_i.getNextSubgoal() - G_i.getPos()
Goal = s_i.getPos() + Dir
if isCollision( s_i.getPos(), Goal ) then
    if isCollision(Goal) then
        Goal = G_i.getNextSubgoal()
    end if
    if isCollision( s_i.getPos(), Goal ) then
        findPath( s_i.getPos(), Goal )
    end if
end if
```

Groups of agents can also perform the same evacuation behavior. The agents within this group then only need to follow along the group evacuation route. A description of this algorithm is shown in Alg. 2.

VII. Direction and Control of Agents

We simulate the control of agents by modeling different forms of direction that may be given to agents as they are undergoing an evacuation. The different forms of direction are described in the following section. They can have vastly different effects on evacuation and being able to simulate these forms of direction is important for a fully interactive evacuation training system.

There are a number of ways that direction can be given to agents. Specifically, as agents are evacuating they may be interested in areas that may be considered dangerous, exits that should be avoided, and exits that should be preferred. In real evacuation situations this can be seen in the form of exits routes posted in buildings or lights representing the direction to evacuate. These could also be physical barriers preventing passage such as a moveable barrier or police tape. Another example of this could be cones or flares set up to direct or alert the agents. These forms of information are easy for humans to process but difficult to simulate.

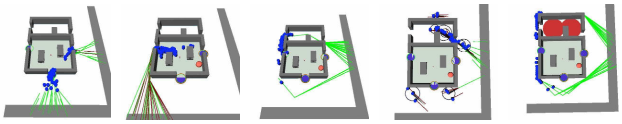
Here we describe two of the main mechanisms necessary to direct or steer the agents:

- **Local:** Barrier or Agent blocking an exit
- **Global:** Relaying global or more complete information

Local direction can be either a barrier or other locally perceived information provided by an agent. There are two ways to achieve local direction. The simplest form of local direction is an obstruction in the environment which can be modeled with an obstacle or obstruction present (i.e., physically preventing passage). In the second form of local direction, a directing agent can represent a barrier to an exit by being placed nearby. It may also represent a sign to indicate an unsafe exit or area nearby. The evacuating agent can then no longer use this exit. An agent is only aware of a barrier when within range of the barrier.

Global direction can be information provided such as a goal location or route guidance beyond the local sensory

TABLE I
DIFFERENT FORMS OF EVACUATION PROBLEM



(a) (b) (c) (d) (e)

Scenario	Evac. Time	Reach Time	$\frac{M}{S}$EX	$\frac{M}{S}$SA	$\frac{D}{S}$SA
(a)	112	164	1.0933	1.1457	1.0010
(b)	176	326	1.1165	1.1454	2.0849
(c)	176	497	1.1138	1.1588	3.1219
(d)	168	688	1.0652	1.1404	3.1955
(e)	176	510	1.0897	1.1499	3.3723

range of the agent. We model global direction by allowing the directing agents to provide the evacuating agents with a subset of full information about specified exits, safe areas or known dangerous areas. The directing agents are equipped with information about the areas that they are directing away from. The directors should also be placed to be able to effectively disperse this direction information. This could be a human or robot directing the evacuating agents.

By being able to give the evacuating agents that encounter directors more global and complete information, better evacuation routes can be selected. We model giving complete information by having the directors make the evacuating agents aware of all the different areas in the environment that the encountered director is aware of. A director may be giving full information to the evacuating agents, however the director may not be aware of all information.

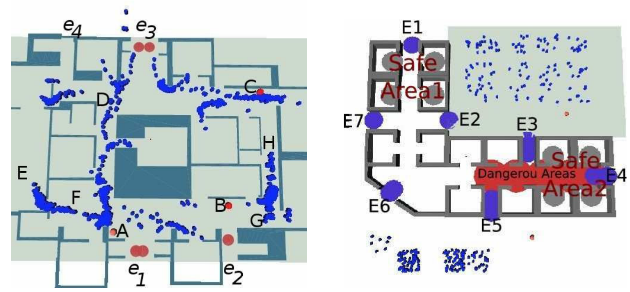
Although we do not currently have directors providing full path information to evacuating agents, we can simulate this by having directing agents equipped with all area information in the environment and provide that to the evacuating agents. In our future work we are interested is studying more intelligent, full evacuation plans that can be generated by directors to improve evacuation which includes testing coordinated movement strategies for the directors and how the directors can plan for the most effective exit usage.

VIII. EXPERIMENTAL RESULTS AND DISCUSSION

We have selected a number of examples to show the versatility of our evacuation planning techniques. The examples range from simple examples used to illustrate our planning potential to more complex and intricate planning scenarios. The time reported is the number of time steps required to have all agents either evacuate the area or reach a predefined safe location averaged over ten trial runs.

A. Rooms Environment

The examples (shown in Table I) illustrate many of the capabilities of our evacuation planning system, some unique to our approach. This environment consists of two rooms with a number of area types available, depending on the scenario. The area types include three exits in the main room, two safe areas (at the bottom and right of the environment), and a potential dangerous area in the second room. Thirty evacuating agents begin the simulation clustered at the center of the lower room. A full evacuation is shown in scenario (a) and in (b)-(e) a director is present to guide evacuation.



(a) Evacuation Variants (b) Regrouping

Fig. 2. Two test environments used: (a) first floor of a building (b) used for Regrouping example.

TABLE II
EVACUATION SCENARIOS WITH VARYING FORMS OF DIRECTION.

Scenario	GE	LE	Evac. Time
E4, D0			1568
E3, D0			1585
E3, D1, LNE1		A	2051
E3, D2, LNE1		A,B	4009
E3, D2, GNE2	A,B		3574
E3, D4, GNE2	A,B,C,D		2215
E3, D5, GNE2	A,B,C,D,E		2182
E3, D3, 1-GNE2, 2-LNE1	F	A,B	3074
E3, D5, 1-GNE2, 4-LNE1	F	A,B,C,H	2188

In scenario (b) the director prevents passage from two exits (on the lower and right walls of the room) resulting in the agents selecting the lower safe area. The director in (c) prevents passage from the same two exits but also relays global information of the lower safe area no longer being available. Scenario (d) is the same as (c) but with grouping of agents. The director in (e) is the same as in (c) and (d), but also relays global information about the dangerous area. While the number of time steps required to evacuate the initial room does not vary much, the amount of time needed to reach the safe area does change depending on the environmental parameters.

The fourth and fifth columns in Table I compare the ratio of minimum distances to the nearest exit or safe area when finding a path using the agent roadmap versus an approximation of the shortest distance. This approximation is computed from a roadmap whose nodes are densely sampled on a grid. The last column is a ratio of the actual distance traveled by the agents compared to the approximate shortest distance to any safe area. This shows that the agents plan in order to satisfy increasing constraints. These ratios also show that the roadmap is adequate in approximating potential paths through the environment.

B. Evacuation Variants

This experiment shows how evacuation can be effected by varying the parameters of the planning problem. We show evacuation results for agents evacuating a building under different conditions. The test environment is the first floor of a building at Texas A&M University, Figure 2(a). Evacuating agents are randomly placed in rooms throughout the building. The agents try to evacuate the building, utilizing the roadmap to find paths to safe areas. We are able to look at many different scenarios. We show experimental results with

500 agents evacuating the first floor, varying the number of available exits, the amount and type of direction given during the evacuation and which exits, if any, are restricted.

In Table II, evacuation under different conditions are shown. E# represents the number of exits available for the evacuating agents to select from. D# is the number of direction points present in the environment directing the agents away from exits (essentially making some exits unavailable). NE# is the number of exits that the direction points are steering evacuating agents away from with L/G used to denote whether the directing agents give local or global information. The GE and LE columns indicate the locations of the global and local directing agents, respectively. Exit locations are shown, labeled e_{1-4}. All the scenarios use e_{1-3} and the first scenario also uses e_4.

Here we try to highlight some of the main results. In the second scenario (noted with LNE1), local direction is provided to evacuating agents in the form of barriers. The information is to avoid the nearest exit. In the case of one directing agent (D1), the barrier blocks one of the main exits and with two directing agents (D2), both lower exits are blocked which results in evacuation through the last available exit. By only giving local information, evacuating agents may end up selecting two bad exits before learning that the last exit is the only exit available. The effect on evacuation can be seen as the evacuation time increases greatly.

We also tested the effects of having directing agents provide global information to the evacuating agents (noted with GNE2). These directing agents inform the evacuating agents of the two exits to avoid. In this way, they are able to act as intelligent directing agents and direct the evacuation to the correct exit in the environment. This creates a better flow during evacuation. The benefits of increasing the number of directing agents can be seen as the evacuation time decreases.

We also tested the evacuation with a mixture of directing agents that provide global and local information. It is interesting to note that by placing local direction at certain locations in the environment and placing the global directing agent in a high traffic area we are able to come close to an evacuation time where five global directors are present.

C. Regrouping to Safe Areas

In this scenario, agents are dispersed around an environment (shown in Figure 2(b)) and regroup to safe locations defined in a building. Evacuation results are shown in Table III for four different scenarios. In the first scenario, the agents regroup to the nearest safe area. In the second example, directing agents are placed at exits $E3$ and $E5$ to simulate a partial blockage of the corridor. The result is that the agents still use both safe areas while not passing through the blocked corridor. In the third and fourth scenario, two advanced directing agents are placed at the locations shown in Figure 2(b) near $E3$ and $E5$. These agents, with a larger alert radius inform evacuating agents to the dangerous areas present in the corridor. The result is that the agents regroup at the safe areas near the upper corridor in the environment.

TABLE III

Scenario	Evac. Time	Reach Time
Basic Regroup	845	1475
Partial blockage of Lower Corridor	1425	2306
Full Block of Lower Corridor	1383	2490
Full Block of Lower Corridor (Grouping)	1448	2747

IX. Conclusions

We have presented a versatile evacuation planning system that can be used to handle a number of scenarios with many key elements unique to our system. We are able to generate evacuation plans that consider agents equipped with different behaviors, capabilities, environmental factors and varying levels of environmental knowledge.

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