

Engineering Smart Behavior in Evacuation Planning using Local Cooperative Path Finding Algorithms and Agent-based Simulations

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Abstract: This paper addresses evacuation problems from the perspective of *cooperative path finding* (CPF). The evacuation problem we call *multi-agent evacuation* (MAE) consists of an undirected graph and a set of agents. The task is to move agents from the endangered part of the graph into the safe part as quickly as possible. Although there exist centralized evacuation algorithms based on network flows that are optimal with respect to various objectives, such algorithms would hardly be applicable in practice since real agents will not be able to follow the centrally created plan. Therefore we designed a local evacuation planning algorithm called LC-MAE based on local CPF techniques. Agent-based simulations in multiple real-life scenarios show that LC-MAE produces solutions that are only worse than the optimum by a small factor. Moreover our approach led to important findings about how many agents need to behave rationally to increase the speed of evacuation.

1 INTRODUCTION

Evacuation planning represents an important real-life problem and is increasingly studied in artificial intelligence (Chalmet et al., 1982; Mishra et al., 2015). The task consists of evacuation of people or other agents from the endangered area into the safe zone.

Various techniques have been applied to address the problem including modeling the problem as *network flows* (Arbib et al., 2018) or nature inspired computation such as *bee colony* optimization.

The map where the evacuation task takes place is often modeled as a graph where vertices represent locations for agents, and edges model the possibility of moving between pairs of locations (Liu et al., 2016). Hence the evacuation problem can be interpreted as a variant of *cooperative path finding* (Silver, 2005; Wang and Botea, 2011; Surynek, 2014; Surynek, 2015) (CPF). Similarly as in CPF, the evacuation modeling must take into account potential collisions between agents and solving techniques must ensure proper avoidance (Foudil et al., 2009). The collision avoidance in CPF is usually represented by a constraint of having at most one agent per vertex. In contrast to CPF, where agents have unique individual goals (locations), we usually do not distinguish between individual agents in the evacuation task. That

is, an agent can evacuate itself to anywhere in the safe zone (not to a specific location in the safe zone).

Another important challenge in evacuation planning is represented by the execution of a plan by real agents. In real-life evacuation scenarios, we cannot simply assume that all agents will want to follow the plan. The real agent may for example prefer the nearest exit while a centrally created plan make it go elsewhere, thus not being realistic for the agent. This differs from classical planning (Ghallab et al., 2016), where the planning authority fully observes the environment, actions are assumed to be deterministic, and plans created in advance are perfectly executed

Therefore we focus on local evacuation planning relying on local cooperative path finding techniques and agent-based simulations. Our assumption is that evacuation paths planned locally using information available to the agent will be more realistic. At the same time we do not rule out the central aspect completely as we also consider some agents to be more informed (about alternative exits, through a communication device) than others.

This paper begins with a formal introduction to the concept of evacuation planning, followed by a short summary of local cooperative path finding algorithms which are the base of our novel evacuation algorithm called Local Cooperative Multi-agent Evacuation (LC-MAE), described and experimentally evaluated in multiple scenarios using agent-based simu-

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lations. As part of the simulations, the algorithm is compared to a network-flow based algorithm which produces near-optimal plans.

2 BACKGROUND

The abstract *multi-agent evacuation problem* (MAE) takes place in an undirected graph $G = (V, E)$ which has vertices divided into a set of *endangered* (D) vertices and a set of *safe* (S) vertices. Agents from a set, $A = \{a_1, a_2, \dots, a_k\}$, are distributed among the vertices and the task is to evacuate them from endangered vertices to safe vertices. This problem is similar to *cooperative path finding* (CPF) (Silver, 2005) from which we took the model for movements of agents.

Each agent is placed in a vertex of G so that there is at most one agent per vertex. The configuration of agents in vertices of the graph at time t will be denoted as $c_t : A \rightarrow V$. Similarly as in CPF an agent can move into a vacant adjacent vertex. Multiple agents can move simultaneously, provided they do not collide with each other (that is, no two agents enter the same target vertex at the same time).

Definition 1. Multi-Agent evacuation (MAE) is a 5-tuple $\mathcal{E} = [G = (V, E), A, c_0, D, S]$, where G represents the environment, A is a set of agents, $c_0 : A \rightarrow V$ is the initial configuration of agents, D and S such that $D \subseteq V$, $S \subseteq V$, $V = D \cup S$ with $D \cap S \neq \emptyset$, and $|S| \geq k$ represent a set of endangered and a set of safe vertices respectively.

The task in MAE is to find a plan that moves all agents into the safe vertices; that is a plan $\pi = [c_0, c_1, \dots, c_m]$ so that $c_m(a) \in S \forall a \in A$. The total time until the last agent reaches the safe zone is called a *makespan*; the makespan of π is m .

To increase chances of evacuation, the makespan should be small. A near makespan-optimal evacuation plan can be found in polynomial time using *network flow* techniques (Yu and LaValle, 2012; Yu and LaValle, 2015; Arbib et al., 2018). However, these algorithms require a centralized approach where agents perfectly follow the central plan which is hardly applicable in real-life evacuation scenarios (Foudil et al., 2009; Hudziak et al., 2015).

3 COOPERATIVE PATH FINDING ALGORITHMS

We address MAE from a local point of view inspired by CPF algorithms like Local Repair A* (LRA*) and Windowed Hierarchical Cooperative A* (WHCA*)

(Silver, 2005). These algorithms feature a *decentralized* approach to multi-agent path finding. Instead of using optimization techniques or network flow, each agent's path is found separately, resolving conflicts between agents trying to enter the same vertex as they occur.

While LRA* only resolves conflicts at the moment agent tries to enter an occupied vertex, a naive strategy which can easily lead to deadlock, WHCA* is more advanced. Instead of only planning their paths in space, agents plan their paths in space-time and share them with other agents using a data structure called *reservation table*. When planning, vertices reserved by another agent at a given time are considered to be impassable.

If each agent planned and reserved its whole path to destination, agents planning later would have information about its complete route and their needs and goals would not be taken into account, leading to selfish behavior and deadlocks. The fix to this behavior is *windowing*, in which agents plan their paths only for a certain, small, number of time units and the planning is staggered, so that each agent has an option of reserving a certain vertex.

4 LOCAL MULTI-AGENT EVACUATION (LC-MAE)

Our new *local multi-agent evacuation* (LC-MAE) algorithm divides the evacuation task into three sub-problems:

- *Evacuation Destination Selection*: The most important difference between MAE and simple CPF is that agents' destinations are not specified.
- *Path-finding to Safety*: Once an agent has picked its destination in S , it has to find a collision-free path to it.
- *Behavior in the Safe Zone*: Agents that have left D do not disappear from the map. They must not block other agents from entering S .

Agent movement in the last two sub-problems is based on modified versions of WHCA* algorithm, described in their respective sections.

4.1 Evacuation Destination Selection

The basic data structure used by LC-MAE when choosing an evacuation destination is the *frontier* denoted F , $F \subseteq S$. The frontier is a set of safe vertices which separates the endangered zone from the safe zone. It holds that an agent must enter S by passing a vertex from F .

In other other words, removing F from G will separate D and S into disconnected components. F is created on algorithm initialization. It holds that an agent must enter S by passing a vertex from F .

Destination selection uses a modified A* algorithm, inspired by the RRA* algorithm (Silver, 2005). Agent's position is set as the path-finding goal, while all nodes in F are added to the initial *open set*. *Manhattan distance* (Korf and Taylor, 1996) is used as the heuristic.

The result is a vertex in F that is located at the shortest true distance from the agent while, at the same time, being reachable by the agent. With the vertex at hand, the algorithm returns its true distance from the agent. This matches many real-world evacuation scenarios in which people are being evacuated from an area they know and thus have a mental map of the nearest exits (Kurdi et al., 2018).

While evacuating, agents track the number of steps they have taken to reach their destination. Since the goal's true distance from the starting position is known, they can compare these two numbers. If the number of steps taken is significantly higher than the distance, it may indicate the agent has veered off the optimal path. This could be, for example, because the path to the chosen destination is congested. In that case, the agent repeats the destination selection process, an action that we call *retargeting*.

4.2 Reservation Table

In LC-MAE we use a variant of the reservation table used in the Cooperative A* algorithm (Silver, 2005). Every vertex in G is associated with a mapping of time steps to reservation structures. Every reservation structure includes a reference to the reserved vertex, the ID of the agent that created the reservation and a priority. Associating priority with reservations is our primary distinguishing feature. Agents can make a reservation for vertex v and time step t provided they fulfill one of the following conditions:

1. No reservation exists yet for v at time t and the vertex can be reserved at time $t + 1$.
2. A lower-priority reservation exists for v at time t and the vertex can be reserved at time $t + 1$.
3. The agent holds a reservation for vertex v at $t - 1$.

Condition 3 ensures that CPF algorithms used in LC-MAE can always perform at least one action, staying in place, without having to dynamically change the order in which agents' paths are planned or performing invalid actions, like colliding with another agent.

The $t + 1$ reservability requirement in conditions 1 and 2 prevents the creation of so-called *trains* - lines or crowds of agents which move in the same direction at the same time and which reduce the simulation realism. A simple example of a train being formed is shown in the right column of figure 1.

4.3 Path-finding To Safety

Once the agent has picked its destination vertex s in S , it plans a path towards s using WHCA* with the RRA* heuristic. An agent plans its path on-demand when it has to return an action for the next time step and fulfills any of these conditions:

- Is more than halfway through its planned path¹
- Has to retarget
- Has lost a reservation for a vertex on its planned path
- Is making its first step

Endangered agents are prioritized relative to agents that are in S - they are processed before agents located in S . This ensures that endangered agents generate their plans first.

As soon as an agent enters S (even if it is not its current destination vertex), it stops following the planned path and switches to the behavior described in the next section.

4.4 Safe Zone Behavior

While some parts of the behavior of an endangered agent, e.g. on-demand planning for a specified number of steps in advance and reserving the vertices for given times do not change once the agents enters a safe zone, the costs for different actions that WHCA* algorithm considers for each step are different and more dynamic.

The major difficulty in the safe zone is that freshly arriving agents must not impede the ongoing evacuation. A simple approach is to move agents as far from D as possible. However, knowing whether an agent is getting away from D is not a trivial problem from the local point of view.

The behavior agents adopt after entering S in LC-MAE (called *surfing*) is based on modified WHCA* algorithm. Costs for the passage from one vertex to another are computed dynamically, depending on the positions of other agents and the type of the agent's target vertex.

¹Only using half of the planned path before replanning is a simple way of improving agent cooperation described in (Silver, 2006)

Algorithm 1: The algorithm for computing the number of agents following agent a .

```

1 previous-reserved ( $\mathcal{E}, \pi, a, t$ )
2   let  $\pi = [c_0, c_1, \dots, c_t]$ 
3    $V_a \leftarrow \{c_{t-b}(a) \mid b = 0, \dots, \frac{t}{2}\}$ 
4   for  $v \in V_a$  do
5     if reserved( $v, t$ ) then
6        $r \leftarrow r + 1$ 
7   return  $r$ 
    
```

The basic idea is that an agent's priorities should vary according to the number of agents following behind, on the same path. When no other agents are following, it will prefer staying in place. With an increasing number of agents behind, the cost of to stay in place will increase.

The agent determines the number of following agents by checking whether there are reservations created for positions it has passed before. The process is formalized in pseudo-code as Algorithm 1.

Since agents only make this check when they start planning their next few steps, the results have to be adjusted to account for the increasing uncertainty about the steps that other agents will take. This is done by subtracting the number of future time steps from the number of following agents (see line 11 of Algorithm 2).

Algorithm 2: Computing costs of different actions for agents in the safe zone. Actions are considered relative to agent a located at v at time t . t_c specifies the time at which the plan is generated.

```

1 neighbors ( $\mathcal{E}, \pi, a, t, v, t_c$ )
2   let  $\pi = [c_0, c_1, \dots, c_t]$ 
3    $A_p \leftarrow \text{previous-reserved}(\mathcal{E}, \pi, a, t_c)$ 
4   costs  $\leftarrow \emptyset$ 
5   for each  $u \in S \mid \{v, u\} \in E$  do
6     if reservable( $u, t + 1$ )  $\wedge u \in S$  then
7       if  $u \in \{c_t(a) \mid t = 0, 1, \dots, t\}$  then
8         costs  $\leftarrow \text{costs} \cup \{(u, 3)\}$ 
9       else
10        costs  $\leftarrow \text{costs} \cup \{(u, 2)\}$ 
11    $b \leftarrow \max(1, |A_p| - (t - t_c))$ 
12   if reservable( $v, t + 1$ ) then
13     costs  $\leftarrow \text{costs} \cup \{(v, 1 * b)\}$ 
14   else
15     costs  $\leftarrow \text{costs} \cup \{(v, 4 * b)\}$ 
16   return costs
    
```

The complete cost-calculation algorithm can be found in Algorithm 2. With increasing back-pressure,

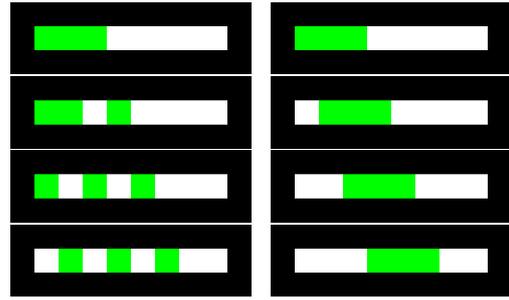


Figure 1: Movement of agents in ordinary MAE (left) and in relaxed MAE (right).

moving into a reservable adjacent vertex becomes the cheapest option. The agent keeps a list of positions it has already visited and assigns them a higher cost. This leads to better diffusion of agents through S as endangered agents can "nudge" safe agents deeper.

5 RELATED WORK - CENTRALIZED EVACUATION

Near optimal solutions of MAE can be found by modeling an MAE instance as network flow (Arbib et al., 2018; Yu and LaValle, 2012) and planning it centrally. The core concept is to construct a time expanded network having m copies of G in which a flow of size $|A|$ exists if and only if the corresponding *relaxed MAE* has a solution of makespan m . In the relaxed MAE we do not require agents to enter vacant vertices, leading to the possibility of movement similar to the right column of figure 1.

The solution for a relaxed MAE problem obtained from the network flow algorithms can be post-processed into a solution of ordinary MAE by postponing moves that would violate the invariant of not entering a vertex that has just been left by an agent. However, postponing moves may lead to deadlocks, so the post-processing algorithm swaps the paths planned for deadlocked agents when a deadlock is detected. We're calling this planning algorithm based on post-processed network flows *POST-MAE*.

6 EXPERIMENTAL EVALUATION

We implemented LC-MAE in Python and evaluated it in multiple benchmark scenarios. We also implemented POST-MAE on top of Push-relabel max-flow algorithm (Goldberg and Tarjan, 1988). In order to estimate the difference between the makespans of plans

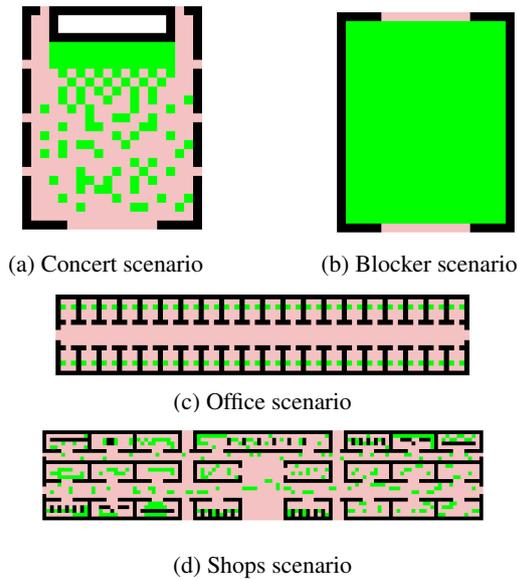


Figure 2: Maps inspired by real-life evacuation scenarios. generated by LC-MAE and makespans of optimal (if completely unrealistic) plans, we also benchmarked POST-MAE without the post-processing, denoted as *flow* in comparison tables. Our implementation relies on data structures implemented in the `networkx` library (Hagberg et al., 2008). The visualization is implemented on top of the `arcade` library (Craven, 2019). In the LC-MAE implementation, the look-ahead window was set to 10 steps.

6.1 Agent Types

To simulate real-life scenarios with higher fidelity we used agents of two types. They differ in their behavior while in S all agents rely on *surfing*. *Retargeting* agents fully implement the destination selection algorithm while *static* agents plan a path to a vertex specified in advance.

6.2 Setup of Experiments

We used 4 different maps in our evaluations as shown in Figure 2 - they represent 4-connected grids with obstacles. Free and safe vertices are white (surrounding area), free and endangered vertices are pink. Vertices occupied by agents are green. Black squares signify walls, so no vertices are present in the underlying graph at those positions.

6.3 Experimental Results

We first compared the makespan of evacuation plans generated by LC-MAE with optimal makespans calculated by the flow-based algorithm for relaxed MAE

Table 1: Makespans for evacuation plans.

Scenario	Agents	LC-MAE	Flow	POST-MAE
Concert	118	90	17	33
Office	80	94	47	62
Shops	299	129	36	75
Blocker	414	146	23	69

and with makespans of solutions post-processed with POST-MAE - see table 1. LC-MAE generates plans that are only worse by a small constant factor (ranging from 1.52 to 2.73) from those generated by POST-MAE, which indicates that LC-MAE solutions are close to the true optimal makespan. Moreover, plans generated by LC-MAE are more realistic as they need local communication only.

The performance of LC-MAE is better than the performance of flow algorithm and than that of POST-MAE, as demonstrated in table 2. An additional advantage is that since LC-MAE is a local algorithm and uses windowing, the plans can be used while they are being generated, since the steps taken by agents do not change.

Table 2: Seconds taken by plan generation.

Scenario	LC-MAE	Flow	POST-MAE	Speedup
Concert	7	52	62	8.9×
Office	4	57	61	15.3×
Shops	20	379	403	20.2×
Blocker	27	220	243	9.0×

6.4 Agent-based Simulations

We also made a series of experiments to understand the real process of evacuation in scenarios in which various types of agents are mixed together, that is, when some agents are better informed than others.

For each map, we created multiple scenarios with some of the retargeting agents replaced by static agents. These static agents try to exit through the largest opening between the safe and endangered zone (which could be described as the main exit from the area) and ignore all other exits. With this setup, retargeting agents could be considered to be better informed, given they take all the possible exits into account.

The percentage of agents that have reached safety as a function of time is shown in Figure 3.

The *Concert* evacuation scenario is one of the scenarios with a large difference in the makespan between the relaxed optimum and the plan generated by LC-MAE.

Our hypothesis is that this is caused by the fact that the side emergency exits are very small and the area behind them quickly becomes crowded with agents that escaped through the emergency exit closest to them.

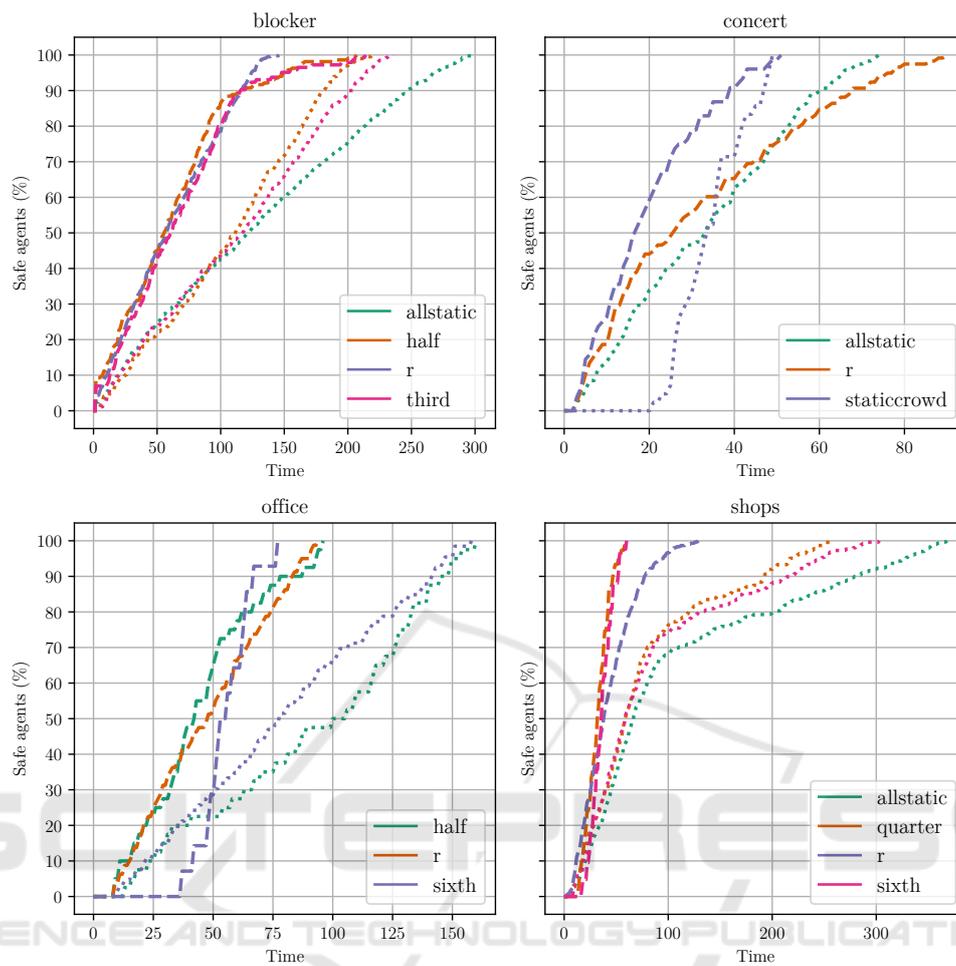


Figure 3: The percentage of safe agents in time. Line colors differentiate between different scenarios. Dashed lines represent percentage of retargeting agents in S , dotted lines represent the percentage of static agents in S .

To test this hypothesis, we created two more scenarios. The first one is called *allstatic* and all the agents are static and try escaping through the large opening in the lower part of the map. In the second one, called *staticcrowd*, only the first three rows in front of the stage are static. The original scenario with all retargeting agents is labeled *r*.

Both *allstatic* and the original version exhibit relatively long makespan, although our hypothesis is confirmed by *allstatic*'s being shorter. The best makespan is exhibited by *staticcrowd*. Retargeting agents use the side exits which do not get overcrowded and leave most of the endangered zone free for static agents to pass through.

In the *Office* scenario we tried two modified versions: *half* and *sixth* - where one half and one sixth of the agents respectively are retargeting, while others are static, trying to escape through the left exit. For the *Shops* scenario, we created three modified ver-

sions where static agents are trying to escape through the large exit at the bottom.

Finally, the *Blocker* scenario best illustrates how static agents can impede the evacuation of retargeting agents. Since exits from the endangered zone are large and there is plenty of safe space on the map, the shortest makespan is achieved when all of the agents are retargeting and the longest when they are all static and try to evacuate through a single exit.

7 CONCLUSION

We presented a new local algorithm called LC-MAE for evacuation of agents in graphs. LC-MAE uses a modification of WHCA* as the underlying path-finding process but also introduces several high-level procedures that guide agents' behaviour depending on whether they are in the endangered or the safe

zone. Our experimental evaluation indicates that LC-MAE generates solutions with makespan that is only a small factor worse than the optimum. We also studied how different ratios of less informed agents affect the process of evacuation. We found that depending on the scenario, the presence of some uninformed agents can improve the evacuation outcome for the well-informed agents. Additionally, even large numbers of uninformed agents don't impede informed agents from reaching the correct exit.

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