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Distributed Multi-Robot Evacuation Incorporating Human Behavior

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Abstract— **When a disaster happens, evacuation in a building can be dangerous. It is well known that trained leaders have an important influence on saving human lives in emergency evacuation. In this paper, we present a novel distributed multi-robot system for guiding people in an emergency evacuation mission. A closed environment, which is represented by the means of Laplacian Artificial Potential Field (LAPF), is considered in the emergency evacuation scenario. A cooperative exit seeking algorithms is designed for the robots to guide evacuees by online estimating the gradient and tracing gradient-descend while maintaining a predefined formation in movement. To better deal with evacuees' behavior in emergency situations, a human panic behavior model is taken into account to the evacuation strategies. Simulations of a single robot team and multi-team are shown to demonstrate our methods for evacuation guidance.**

I. INTRODUCTION

In a disaster, such as fire, toxic gas leak, and earthquake, an effective emergency evacuation guidance plays a significant role in helping people escape from buildings. The benefits of evacuation guidance include saving the evacuation time, shorting the travel distance, and reducing the congestion in the evacuation process. In a real fire, the situation of smoke and alarms can make occupants panic and stampede to exits which result in injuries and even deaths. For people who have incomplete knowledge of the area or first time visitors, the result is more worse. Evacuation guidance is also important for occupants who may know the escape route when something unexpected happens, such as impassable route or severe congestion in the main exit. In this case, occupants need to be guided to a second best available exit. Evacuation robots can be used to implement this emergency evacuation guidance mission. These robots could be stored in the strategic places inside of large buildings and be invoked along with fire alarms when the building needs to be evacuated [1].

Emergency evacuation problems have been studied by computer simulation [2], [3] and mathematical analysis [4], [5], [6]. Computer simulation provides a tool for analyzing and assessing the level of safety for human life. It is essential to verify the results of simulations [2]. Mathematical analysis is to pre-compute evacuation plans in order to have a good response in an emergency situation [4]. It is usually to solve a multiobjective optimization problem that several objective functions are brought into consideration and need to be satisfied simultaneously, though these objective functions may often conflict with each other [5].

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Developing social and cooperative robots for guiding a group of people in emergency evacuation mission is a novel idea in the field. Some related research in using multi-robot for guiding people are [1], [7], [8]. Robinette and Howard [1] proposed a model of human panic behavior for robotic based emergency evacuation, and presented simulation results that a significantly large proportion of people are evacuated with robot assistance than without. But these robots do not work cooperatively and the robot behaviors need to be improved, such as searching and interacting with humans. Garrell *et.al* [7] presented a discrete time motion model for guiding people in urban areas using multiple robots. Their method deals with large environments with obstacles and regrouping people who left the group. From the point of the benefits of evacuation guidance, it is not specifically designed for emergency evacuation guidance, although they believe it can be used. Furthermore, they adopted the social force model for dynamic pedestrian model [9] which may not suit the emergency situations. In [8], Garrell and Sanfeliu go one step ahead, presenting an approach for computing robot's local optimal trajectories in guiding and regrouping people mission. There are also some research using a single robot for guiding people, such as companion robot [10], museum tour-guide robot [11] and tour-talking robot [12].

In this paper, we present a distributed multi-robot system for emergency evacuation guidance in a closed building. To better deal with realistic emergency situations, a model of human panic behavior is considered. The human panic behavior model provides us a good understanding of human's reactions in emergency situations which facilitates the design of evacuation algorithms. We design two algorithms for evacuation robot team behavior, single team and multiple teams, both of which incorporate the model of human panic behavior. In a single evacuation robot team, one robot is assigned as the leader role, and other robots are the shepherds. Both the leader and the shepherds work cooperatively and are responsible for searching evacuees and guiding them to exit. For multiple teams, the leader of each team is able to communicate with other teams' leaders for updating real time destination information.

The environment is presented by means of a Laplacian Artificial Potential Field (LAPF) [13], as this method does not exhibit local minima which plague the potential field method. Once the potential function is computed, the exit potential map, which has the potential value of every point in the environment, is built. The exit has the global minimum potential value which has an attractive force to robots. Through on-board indoor positioning systems, the robots can locate themselves and get the current potential value by checking the map. A cooperative exit seeking algorithm is proposed based on the LAPF method. Each robot in an evacuation guidance robot team needs to make estimation of the gradient and then follows the gradient-descending direction to the exit. In a realistic multi-exit environment, each exit has a potential map. The robot team will only choose the potential map of the best available exit in the evacuation guidance mission. Only when the preferred exit is impassable, the team continues to seek another available exit. Two simulation scenarios, single-team and multi-team evacuation guidance, are presented to validate our proposed methods.

The contribution of this paper is twofold. First, we design a cooperative exit seeking algorithm based on online cooperative gradient estimation to guide people in emergency evacuation mission. Second, the proposed algorithms for evacuation robots incorporate a model of human panic behavior which can effectively guide clustered people to a safe zone.

The rest of the paper is organized as follows. Section II gives the models of human panic behavior and evacuation robot behavior. In Section III, a cooperative exit seeking algorithm is proposed, which estimates the gradient cooperatively, follows the gradient-descending direction, and maintain a formation to move towards exit. Simulation results of a single team and multi-team evacuation guidance are described in Section IV. Finally, conclusion is presented in Section V.

II. SYSTEM ARCHITECTURE

A. Model Human Panic Behavior

We propose a model which is inspired from the work of Robinette and Howard [1] to simulate human behaviors in the emergency situation, as shown in Fig. 1. It includes human reactions, such as panic, move towards exits or exit signs, follow evacuation robot and find other humans. This model indicates that humans spontaneously follow the rule in each situation. It is straightforward that the behavior of going to exit is always the highest priority. All evacuees want to escape from the fire emergency as soon as possible.

The second priority behavior is humans following the evacuation robots once the robots are seen. In this paper, we assign robots as "exit signs". This behavior means humans are likely to move towards to exit sign in order to find an exit. When humans have no clue on where to go due to both exit and exit sign are not seen, the third priority behavior is that people tend to crowd together to increase probability of finding an exit. This could explain why congestion often happens in emergency evacuation. When assistance is not available, people prefer to cluster with each other or follow the group. The lowest priority behavior is people being alarmed. In this situation, none of the exits, robots and humans are available to help, and people move randomly in panic.

There are some existing works on studying people's motion [14], [9]. In [14], a mathematic model for the behaviors of pedestrians is proposed. In [9], social force model for

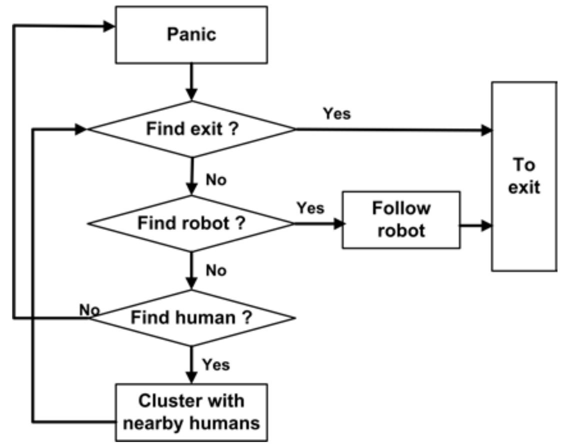

Fig. 1: Human Panic Behavior Model

dynamic pedestrian model is studied. In [7], a people guidance model is proposed which considers regrouping people who left the group. All the above mentioned methods model people in non-emergency circumstances. In our evacuation scenario, the robots are assigned as exits signs. So evacuees are highly possible to stay in a group instead of escaping from the group.

In this paper, we adopt the concept of human-robot interaction zones, which are discussed in [15]. They are the intimate zone (0 to 0.46 meters), the personal zone (0.46 to 1.22 meters), the social zone (1.22 to 3.66 meters) and the public zone (further than 3.6 meters). We consider the robots stay in the social zone and evacuees can stay between the personal zone and the social zone.

Algorithm 1: People motion model
1. If dist (myPosition, nearestExit)<20, Goal=nearestExit.
2. Else if dist (myPosition, nearestRobot)<20, Goal=formation area.
3. Else if dist (myPosition, nearestHuman)<10, Goal=humancentroid.
4. Else Goal=randomPoint.

From **Algorithm 1**, people will first check if there is a exit with 20 units. If there is, people will move to exit without hesitation. Otherwise, people will try to look for the exit sign (robot). Once an evacuation robot team is found, people will move towards it. If there is no exit or exit sign, people will cluster with neighbors. The lowest priority behavior is panic behavior that people move randomly.

B. Evacuation Robot Behavior

The model of the evacuation robot behavior is described in Fig. 2. The evacuation robot team will first choose the nearest exit as the destination. The highest priority task for an evacuation robot team is to search evacuees. From aforementioned human panic behavior, we know evacuees will also tend to follow the evacuation robots once the robots are seen by people. The robots are equipped sensors such as cameras to detect people. We assume that people and robot can recognize each other in the same distance. Once people is found, the robot team will wait for people. People will treat the robot as an exit sign and head directly towards it. The guiding behavior will not be invoked until evacuees are in the social zone of the robot team. Then the robot team continuous to move to the exit while searching unassisted people. If the robot team reaches the exit and it is passable, the robot team will stop. If the robot team finds the exit is impassable, the robot team will choose another exit as a new destination.

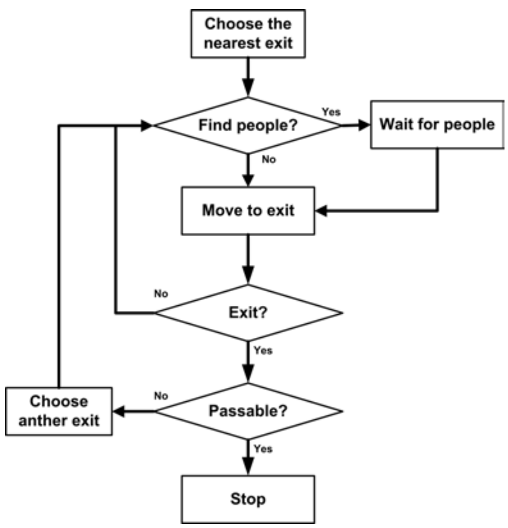

Fig. 2: Evacuation robot team behavior

We consider two robot roles in an evacuation robot team. One robot is assigned as the leader and other robots are shepherds. Both the leader and the shepherds have the responsibility to guide people to evacuate to the exit. But only the leader can decide the destination. Two algorithms (**Algorithms 2 and 3**) for evacuation robot team guidance are presented. One is for single evacuation robot team guidance and the other one is multi-team coordination algorithm.

In **Algorithm 2**, the leader of the evacuation robot team will first choose the nearest exit as the destination and execute the corresponded exit potential map. The shepherds will follow their leader and use the same exit potential field map. Once the robot team detects unassisted people within 20 units, it will wait for people until everyone is within 5 units of the robot team. Then the robot team will continue to move to the exit while searching unassisted people. If the exit is within 20 units of the robot team, we consider that the robot team reaches the exit. If the exit is passable, the robot team will stop. Otherwise, the leader will choose another exit as the new destination and the robot team will go to step 2.

To improve the efficiency of evacuation, we employ multiple evacuation robot teams (stored in the strategic places in the environment) to guide people to evacuate from emergency. **Algorithm 3** is proposed to coordinate multiple teams. In this case, when some routes are impassable in emergencies, the leader can check the update message from other teams' leaders to see the availability of current exit and then decide if the leader needs to choose another exit.

Algorithm 2: Single evacuation robot team guidance

1. Choose the nearest exit.
2. If dist 5<(human, robot)<20,
   Wait for human.
3. Else move to the exit.
4. If 20<dist(robot, exit),
   Go to step 2.
5. Else if the exit is passable,
   Stop.
6. Else choose another exit and then go to step 2.

From **Algorithm 3**, we can see that each robot team will compute the path based on the chosen exit potential field map and move to the exit at step 1. Initially, the robot team will select the nearest exit as the destination. At step 2, if the robot team reaches the exit and the exit is passable, the leader will broadcast that the exit is available and then stop. If the robot team reaches the exit but the exit is impassable, the leader will broadcast the impassable message to other leaders and then choose another exit. At step 3, the leader will check if there is any update message from other leaders. If the impassability of the current exit is reported, the leader will choose the best one from the available exits. Otherwise, the robot team will execute step 1.

Algorithm 3: Multiple teams coordination algorithm

1. Compute the path and move to the exit.
2. If the team reaches the exit,
   If the exit is passable,
   Broadcast the passable message to other leaders and stop.
   Else broadcast the impassable message to other leaders,
   choose another exit, and go to step 1.
3. Else check the messages from other leaders.
4. If the impassability of the current exit is reported,
   Choose another exit and go to step 1.
5. Else go to step 1.

III. Cooperative Exit Seeking Algorithm

In this section, we will first discuss the LAPF method that we use to present the environment of a bounded area with obstacles. Then a new cooperative exit seeking algorithm is presented for a robot team to cooperatively estimate gradient, form a formation, and move gradient-descending towards the exit.

We use LAPF to represent the environment.The advantage of LAPF is that it can guarantee the global minimum and to avoid the local minimum. Due to computational expenses, we assume that the potential functions are pre-computed, so the exit potential map, which has the potential value of every point in the environment, is preloaded as a map on the robots, as shown in Fig. 3. The exit (red square) has the global minimum potential value which has an attractive potential to the robots. Through on-board indoor positioning systems, the robots can locate themselves and get the potential value by checking the map. The exit potential map will be used to find a path to exit for the robots. In a multi-exit environment, which is more realistic, each exit has a potential map. The leader will only choose the best available one from the exit potential maps in evacuation guidance mission. The detailed control strategies are explained in the following.

We assign two roles for an evacuation guidance robot team: one robot is assigned as the leader role and the others are shepherds. The leader and the shepherds evenly take the responsibility for guiding people evacuating to the exit. The difference between them is that the leader has the ability to communicate with other teams' leaders and make a decision of executing which exit potential field map in a multi-exit environment.

We assume that the robot's motion can be described by a double integrator:

$$\begin{aligned} \dot{\mathbf{x}}_i &= \mathbf{v}_i \\ \dot{\mathbf{v}}_i &= \mathbf{u}_i \quad for\ i = 1, 2, \ldots, n \end{aligned} \tag{1}$$

where $\mathbf{x}_i \in \mathbb{R}^2$,$\mathbf{v}_i \in \mathbb{R}^2$ and $\mathbf{u}_i \in \mathbb{R}^2$ are the position, the velocity and the control input (acceleration) of the ith robot in a 2-dimensional workspace.

Since the robots are equipped with indoor positioning systems and know the potential value measurement (instead of gradient), each robot needs to make estimation of the gradient and then follows the gradient direction to the exit. In this section, we use a Lease Square (LS) estimator for gradient estimation.

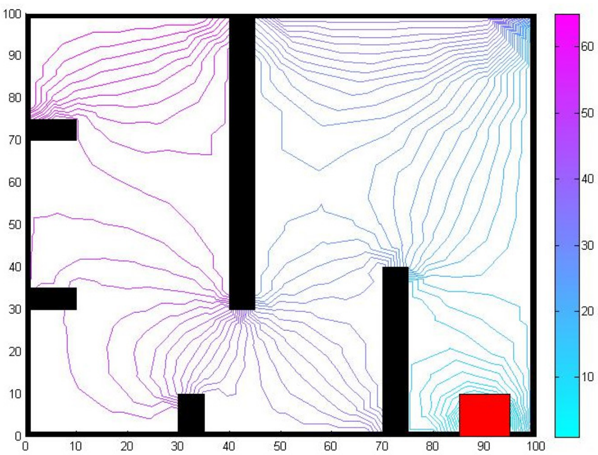

Fig. 3: The environment created using LAPF

The exit potential field map has a scalar valued distribution function $P(\mathbf{x})$ with respect to $\mathbf{x}$ and reaches its global minimum at $\mathbf{x} = \mathbf{x}_{exit}$, which is the position of the exit in the map. The measurement of $P(\mathbf{x})$ are different for robots locating at different positions. Our goal is to drive the evacuation robots to the exit position $\mathbf{x}_{exit}$ in a desired formation. To solve this cooperative exit seeking problem, we design two behaviors for the robot: one is the gradient descending behavior, which steers the robots to the exit, and the other one is the formation maintaining behavior, which maintains the desired formation for entrapping evacuees. We assume the formation area has a drag force that will attract evacuees within it and then they will not escape from it but follow the robots.

A. Estimation of gradient

In this section, we use a LS estimator for gradient estimation. Our goal is to estimate the gradient at $\mathbf{x}_c(t)$, which is the center of formation, i.e., $\mathbf{x}_c(t) = \frac{1}{n}\sum_1^n \mathbf{x}_i(t)$, based on the sampling of $P(\mathbf{x})$, where n is the number of robots in the group.

$$\hat{\mathbf{y}} = \begin{bmatrix} \mathbf{X}(t) & \mathbf{1} \end{bmatrix} \theta(t) \tag{2}$$

with

$$\hat{\mathbf{y}}(t) = \begin{bmatrix} \hat{P}(\mathbf{x}_1(t)) \\ \hat{P}(\mathbf{x}_2(t)) \\ \ldots \\ \hat{P}(\mathbf{x}_n)(t) \end{bmatrix}, \mathbf{X} = \begin{bmatrix} \mathbf{x}_1^T(t) \\ \mathbf{x}_2^T(t) \\ \ldots \\ \mathbf{x}_n^T(t) \end{bmatrix} \tag{3}$$

where $\mathbf{x}_1(t), \mathbf{x}_2(t), \ldots, \mathbf{x}_n(t)$ are all 2×1 vectors, $\theta(t)$ is the estimation parameter, which is a 3×1 vector, $\hat{\mathbf{y}}$ is the estimation of $\mathbf{y}(\mathbf{x}_i)$, and $\mathbf{1}$ is a $n \times 1$ vector with all elements are 1. The estimation error can be described by the difference between the estimation $\hat{\mathbf{y}}(\mathbf{x}_i)$ and $\mathbf{y}(\mathbf{x}_i)$. We use the LS estimation method to minimize the differences, that is

$$minV = \|\hat{\mathbf{y}} - \mathbf{y}\|^2 \tag{4}$$

By solving the $minV$, we get

$$\theta = \begin{bmatrix} \mathbf{X}^T(t)\mathbf{X}(t) & \mathbf{X}^T(t)\mathbf{1} \\ \mathbf{1}^T\mathbf{X}(t) & \mathbf{1}^T\mathbf{1} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{X}^T(t) \\ \mathbf{1}^T \end{bmatrix} \mathbf{y}(t) \tag{5}$$

$$\hat{\mathbf{g}}_c(t) = \begin{bmatrix} \mathbf{I} & \mathbf{0} \end{bmatrix} \theta(t) \tag{6}$$

where $\hat{\mathbf{g}}_c(t)$ is the gradient estimation at the formation center $\mathbf{x}_c(t)$ at time t and $\mathbf{I}$ is a 2×2 identity matrix. $\mathbf{1}$ is a 2-row vector with all entries equal to 1, and $\mathbf{0}$ is a 2-row vector with all entries equal to 0. This equation provides us an optimal estimation of $\hat{\mathbf{g}}_c(t)$ is the sense of least squares.

B. Cooperative control algorithm

We present the following control input to the ith robot,

$$\begin{aligned} \mathbf{u}_i = &- \sum_{j \in \mathbb{N}(i)} \omega_{1ij}(\mathbf{x}_i - \mathbf{x}_j - \mathbf{x}_{di} + \mathbf{x}_{dj}) \\ &- c_0 \hat{\mathbf{g}}_c - \sum_{j \in \mathbb{N}(i)} \omega_{2ij}(\mathbf{v}_i - \mathbf{v}_j) \end{aligned} \tag{7}$$

where $\mathbb{N}(i)$ denotes the neighbor set of the ith robot, $\omega_{1ij} = \omega_{1ji}$ and $\omega_{2ij} = \omega_{2ji}$, which are positive constants, c_0 is also positive constant, and $\mathbf{x}_{di}$ is the desired relative position of the ith robot in the desired formation. $\hat{\mathbf{g}}_c$ is the gradient estimation.

The first term in the control law , $(\mathbf{x}_i - \mathbf{x}_j - \mathbf{x}_{di} + \mathbf{x}_{dj})$ is the difference from the real relative positions to the desired virtual structure. When $t \to \infty$, $\mathbf{x}_i \to \mathbf{x}_{di}$ and $\mathbf{x}_j \to \mathbf{x}_{dj}$. This term drives the robots to the desired formation. The second term generates the gradient descending movement. The third term, $(\mathbf{v}_i - \mathbf{v}_j)$ is the velocity difference between robots. When $t \to \infty$, $\mathbf{v}_i \to \mathbf{v}_j$. The detailed convergence proof can be found in our previous work [16].

IV. SIMULATIONS

We conducted two different experiments. One is single evacuation robot team guidance and the other one is multiple evacuation robot team guidance. We consider a group of 3 robots as an evacuation guidance team. One of them is leader and two other robots are shepherds. The leader will choose the best exit (nearest one) as the destination and execute the corresponded exit potential map. The shepherds will follow their leader to use the same exit potential field map. All robots adopt the cooperative exit seeking algorithm that is described in section III to find the path to the exit. All evacuees will follow the human panic behavior model described in Section II. A.

In the first experiment, we present the scenario of single evacuation robot team guidance. An evacuation robot team (3 robots) evacuated 6 evacuees to the exit while maintained a circle formation. The robot team follows **Algorithm 2** and evacuees are randomly distributed in the LAPF environment with 100 by 100 unit. Figure 4 shows the different time instances of the simulation process. The position of the robots are plotted with small red square and the evacuees are represented by blue circles. The big red square in right bottom corner is the exit. In Fig. 4(a), 2 evacuees are detected by the robot team. The evacuation team will not move to the exit until two evacuees are entrapped into the circle. Meanwhile, 4 other evacuees are moving follow the human panic behavior model. In Fig. 4(b), (c) the evacuation team continuous to move to the exit because no evacuee is found. At the meantime, 4 other evacuees are clustered together which is one of the behaviors in the human panic behavior model. Then all 6 evacuees have been entrapped into the circle, as shown in Fig. 4(d). Next, the evacuation robot team guides 6 evacuees to evacuate to the exit and reach it, the process is shown by Fig. 4(e), (f), (g) and (h). The path of the center of the robot team is shown in solid line in the figure.

In the second experiment, we present that two evacuation robot teams (6 robots) implement an evacuation guidance mission according to **Algorithm 3** in a large area (100×200) with two exits. The different time instances of the simulation process is shown in Fig. 5. At the beginning, the robot team 1 and team 2 choose the exit 1 and exit 2 as their respective destinations. Fig. 5(a), (b), (c), and (d) show the process of two robot teams evacuating people to the exit 1 and exit 2, respectively. It is similar to the process of single robot team evacuation guidance. In Fig. 5(e), both the robot team 1 and team 2 reach their destination. However, the robot team 1 finds that exit 1 is impassable. Meanwhile, exit 2's availability is confirmed by team 2. Fig. 5(f), (g), and (h) show that team 1 chooses exit 2 as a new destination and reaches it finally. The path of the center of the robot team is shown in solid line in the figure.

The above two experiments demonstrated our proposed method. The desired performances are shown using our cooperative control strategy incorporated with **Algorithms 1**, **2**, and **3**.

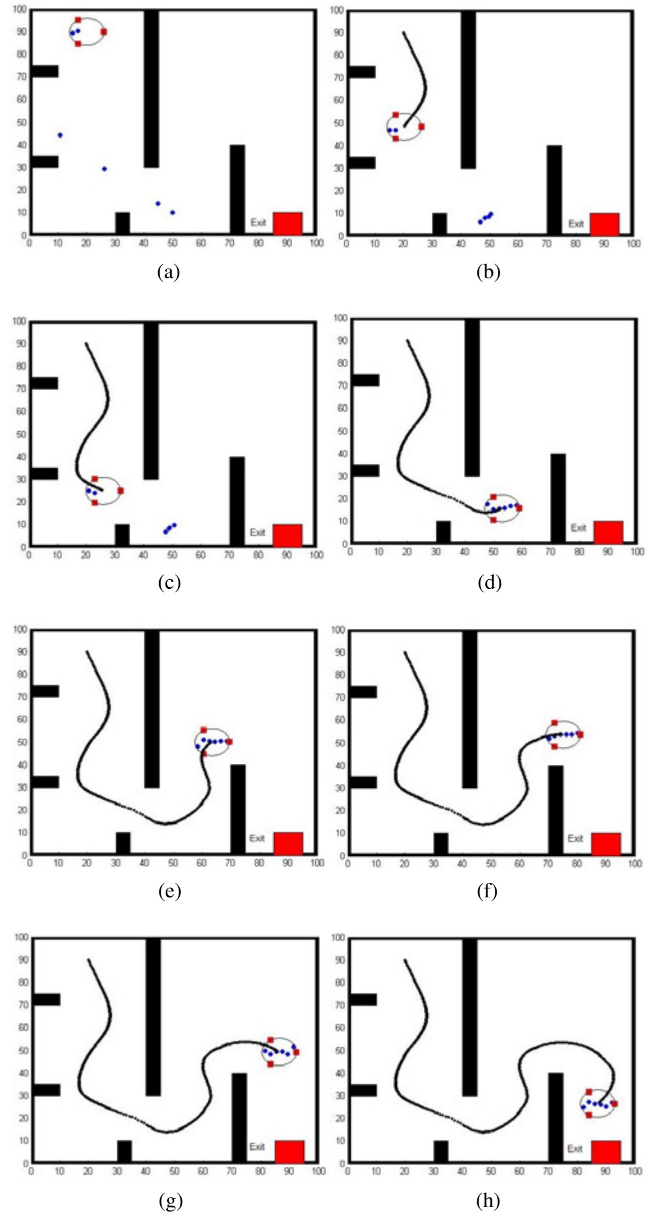

Fig. 4: A single robot team guides people to evacuate to the exit.

V. CONCLUSIONS

We have presented a novel distributed multi-robot system for guiding people evacuation in emergency situations. A cooperative exit seeking algorithm is proposed based on a LAPF map. Two simulation scenarios are shown by means of the cooperative control strategy incorporating human panic model **Algorithm 1**, single evacuation robot team behavior **Algorithm 2**, and multi-team coordination **Algorithm 3**. The results demonstrate the proposed method can be used to guide people to evacuate to exits in emergency situations.

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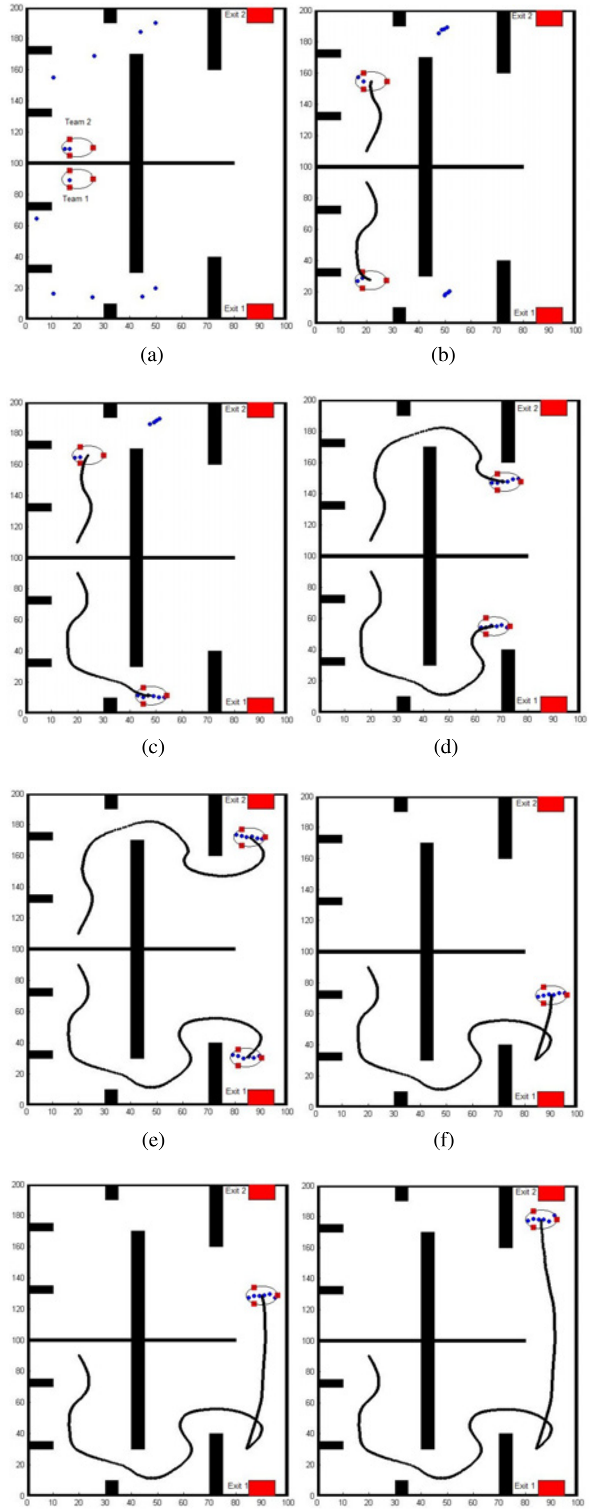

(a) (b) (c) (d) (e) (f) (g) (h)

Fig. 5: Two robot teams in the evacuation guidance mission.