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Local Optimization of Cooperative Robot Movements for Guiding and Regrouping People in a Guiding Mission

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Abstract— **This article presents a novel approach for optimizing locally the work of cooperative robots and obtaining the minimum displacement of humans in a guiding people mission. Unlike other methods, we consider situations where individuals can move freely and can escape from the formation, moreover they must be regrouped by multiple mobile robots working cooperatively. The problem is addressed by introducing a "Discrete Time Motion" model (DTM) and a new cost function that minimizes the work required by robots for leading and regrouping people. The guiding mission is carried out in urban areas containing multiple obstacles and building constraints. Furthermore, an analysis of forces actuating among robots and humans is presented throughout simulations of different situations of robot and human configurations and behaviors.**

I. Introduction

Nowadays, robotics area has increased significantly in different fields, nevertheless the branch of social robotics has captured the attention of many researchers which have proposed diverse applications such as cooperative exploration [7], people evacuation [16] or robots companion [5], among others. Recently, there is an interesting and challenging "problem" that involves social and cooperative robotics. It consists of guiding a group of people using mobile robots and network robotics technologies that work cooperatively. Different authors have developed works in order to lead people in bounded environments, such as hospitals or museums [2], or groups of animals [13].

In previous work [8], a model for guiding people in a dynamic environment using several robots working in a cooperative way was presented. This model is called "Discrete Time Motion" (DTM), which is used to represent people and robot motions. The DTM predicts people and robot movements and gives the motion instructions to robots. DTM uses a Particle Filter formulation [1], with the particularity that it incorporates realistic human motion models. The model assumes that obstacles, people and robots are modeled by potential functions.

In this research, we go one step ahead, presenting a method to optimize locally the tasks assignment to robots for doing their missions. Robots' assignation are done by analyzing the minimum work required to do such task, where the function to minimize is based on one hand, by robot's motion, and, on the other hand, by the impact of such motions on people's displacement. The first term takes into account the work needed to move a robot from an origin to a destination, whereas the second term analyzes the impact that robots have on people to be moved, and its computation uses the formulation of Helbing et al. [10].

To compute robot's local optimal trajectories the method estimates robots' future positions, individuals' positions and obtain optimal trajectories according to people distribution on urban area. The computation of robots impact on people is done by forces that appear between robots and humans, and between humans and humans.

In the remainder of the paper, we start by discussing the related work in Section II. Section III describes the forces that actuate in the task, and how to compute the optimal way to solve the cooperative robots' tasks based on the minimum work, different configurations and distributions of robots. Computation of configurations for group reunification is presented in Section IV. Experiments and Results are presented in Section V and the conclusions in Section VI.

II. Related Work

The interaction between social robotics and cooperative robotics areas is a new field of study. Therefore, the number of publications that exist nowadays is quiet short, specifically, if we refer to the study of guiding a group of people in urban areas with several robots. We can find some works presented by Burgard et al. in the literature using a single robot leading people in exhibitions and museums [2], or in hospitals or acting as an assistant [5] done by Dautenhahn et al. Nevertheless, the main purpose of these robots were educational or entertainment, instead of guiding groups. Casper et al. presented similar applications which have been developed for evacuating emergency areas, detecting hazardous materials or offering human assistance [3], but these robots were not specifically designed for guiding people, and they do not, thus, behave in a cooperative way. Another example is the interaction with animal flocks, Vaughan presented some research where flocks automatically has been controlled by using a single robot [13], [15]. Again, the cooperative behavior of our approach is not exploited in these methods,

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and the environment where the systems are shown to work are highly controlled, and they do not include obstacles.

All the methods mentioned above consider either single robots, or multiple robots moving independently from the rest. To our knowledge, only a few works deal with multiple robots behaving in a cooperative mode. A first work, from Martinez et al. [6], performs a qualitative analysis of the movements of different entities and build an architecture of three robots to guide them. However, realistic situations, such as obstacles or dealing with individuals leaving the group are not considered. In [11] Lien et al. consider several types of robot formations and different robot strategies for approaching to people. Nonetheless, all these issues and the general movements of robots are ruled by a large number of heuristics which makes the system impractical.

Pedestrian motion studies have been carried out experimentally and by simulation. Pedestrian simulation is a representation of pedestrian motion using a set of mathematical models that can be used to evaluate the pedestrian motions in different situations. Helbing has done research in force model [10]. Pedestrian motion analysis can be divided into two levels: macroscopic and microscopic. The first one, the macroscopic level, studies the space allocation of people in the pedestrian facilities [12]. The second one, the microscopic level, investigates pedestrian's motion individually. In our work we are interested in microscopic level, every individual in the group is considered individually.

In the following section we will describe how we compute the best task assignment, using a cost function, of the robots to guide a group of people using several robots behaving in a cooperative manner.

III. Definition of the Optimal Robot Task Assignment for the Cooperative Mission

In our previous work [8], we used two robots working in a cooperative way, one as a tour guide (the leader robot) and the other one, as a shepherd robot. The mission of the leader robot was to guide a group of people from an origin to a destination. The other robot was used as an assistant based on shepherd dog theory [4], [11] and its objective was to regroup people who escape from the the crowd formation. The strategy followed in the mentioned work, was, firstly, the computation of the estimate people's velocity with a particle filter [1], and secondly, it calculates the optimal path from the shepherd robot to the estimated position of people that are moving away.

In this work we analyze which is the best strategy in the following situation: "Given a fixed number of robots (usually 2 or 3), assign robots' tasks that will minimize the work required by them, and, also, will produce the minimum displacement problems for guiding people".

The cost function, described below, speaks in Work terms, and it can be divided into two blocks: *(i)* Robot work motion, and *(ii)* Human work motion.

In order to know what robots' tasks are, we have considered the following situations: *(i)* The leader robot has to guide people, *(ii)* One robot has to look for the person (or people) that can potentially escape from the crowd formation and push him (or them) to regroup him (or them) into group, *(iii)* one robot has to go behind the people in order to push them in case that the crowd formation is broken down.

Nonetheless, robots must be able to solve all this task while they are navigating and avoiding obstacles and do not infer in people's living space. Furthermore, there are other situations that can happen, however they have not been considered in this present work, for instance, one robot is used as a barrier in a corner.

In case that we use two robots, one will be the leader and the second one will do the tasks of regrouping and pushing the people. If we consider three robots, one will be the leader, and the other two will be used for regrouping or pushing people. It is not predefined which robot will be the leader, indeed the robots can interchange their roles depending on the evaluation of the cost function. The Robot tasks that we are considering are:

- *Leader task*: Firstly the leader robot computes a path planning and moves to the next point. We also assume that there exists a *drag force* that will attract people behind the robot. Here, the robot has only to move from the present position to the next one of the guiding path. In case that a robot, that is not the leader, takes its role, this robot will have first to move still leader's present position and then carry out this task.
- *Looking for a person that goes away task*: The robot moves to the estimated position of the individual who goes away from the crowd formation. In this case, the robot has to compute all possible paths to reach the estimate position and then, take the one which minimize the itinerary. In our simulations, we have considered a selections of points on the environment where people have a strong probability to scape.
- *Pushing task*: The robot pushes a person that has gone away in order to reach the crowd formation. This task can be also applied when a robot pushes a person (or people) who is (are) going behind the crowd formation in order to regroup people when the formation is broken down. We assume that there exists a repulsion force that pushes the person to follow the direction of the robot.
- *Crowd traversing task*: The robot has to move through the formation to achieve the estimated position of the person that goes away from the crowd formation. This task implies that the robot has to push people away from their path, which creates a set of repulsion forces from the robot to people. In this work we are not taken into account this situation, due to safety reasons.

In order to compute the dragging, pushing and crowd traversing forces, we use the equations defined in previous works on human behavior with other individuals [10]. People movements are determined by their desired speed and the goal they wish to reach. In our case, the direction of the person movement $\vec{e}_i(t)$ is given by:

$$\vec{e}_i(t) = \vec{e}_{robot}(t) + \vec{u}(t) \quad (1)$$

where $\vec{u}$ is the noise. Usually, people do not have a concrete goal and should follow the leader robot, thus, its direction is determined by the robot's movement or the individual that they have in front, if the robot is not in their visual field.

In following sections we will describe the different forces for the computation of the cost function.

A. Robot Work Motion

Working with autonomous mobile robots, the robot i work motion is expressed by:

$$f_i^{mot} = m_i a_i \tag{2}$$

$$W_i^{mot} = f_i^{mot} \Delta s_i \tag{3}$$

where m_i is the mass of the i-th robot, a_i its acceleration and Δx_i the space traversed by the robot to achieve its goal.

B. Human Work Motion

In Human Robot Interaction, it is necessary to consider the *dragging*, *pushing* and *crowd intrusion forces* that robot's motion produces and that can affect to people. This component is called *Human Work Motion*, and it is the expense of people's movements as a result of robot's motions. As it has been mentioned several times in this paper, the group follows the robot guide/leader, and there is a set of robots that help to achieve their goal. The effect of robots on people as forces is as follows:

- leader robot: attractive (dragging) force, it is inversely proportional to the distance, until a certain distance.
- shepherding robot: Repulsive (pushing, traversing) force, has a repulsive effect inside people's living space.

1) Dragging Work: The dragging force is necessary when the leader robot guides the group of people from one place to another. It acts as an attractive force, hence the force applied by robot leader i to each person j is:

$$f_{ij}^{drag}(t) = -C_{ij}\vec{n_{ij}}(t) = -C_{ij}\frac{x_i(t)-x_j(t)}{d_{ij}(t)} \tag{4}$$

$$d_{ij}(t) = \left\|x_i(t)-x_j(t)\right\| \tag{5}$$

where $d_{ij}(t)$ is the normalizated vector pointing from person j to robot i at instant t. See [9] for more information about the parameter C_{ij} , which reflects the attraction coefficient over the individual j, and it depends on the distance between the robot leader and person j.

Thus, the dragging work that robot leader applied to each individual is defined by:

$$W_{drag} = \sum_{\forall \text{ person j}} f_{ij}^{drag}\Delta s_j \tag{6}$$

Where Δs_j is the distance traveled by the person j.

2) Pushing Work: The *Pushing force* is given by the repulsive effect developed by shepherding robot on the group of people, for regrouping a person (or the broken crowd) in the main crowd formation. This repulsive force is due by the intrusion of the robot in the people's living space, which is five feet around humans. The territorial effect may be described as a repulsive social force:

$$f_{ij}^{push} = A_i exp^{(r_{ij}-d_{ij})/B_i}\vec{n_{ij}}\left(\lambda_i + (1+\lambda_i)\frac{1+cos(\varphi_{ij})}{2}\right) \tag{7}$$

Where A_i is the interaction strength, $r_{ij} = r_i + r_j$ the sum of the radiis of robot i and person j, usually people has radii of one meter, and robots 1.5 m, B_i parameter of repulsive interaction, $d_{ij}(t) = \left\|x_i(t)-x_j(t)\right\|$ is the distance of the mass center of robot i and person j. Finally, with the choice $\lambda < 1$, the parameter reflects the situation in front of a pedestrian has a larger impact on his behavior than things happening behind. The angle $\varphi_{ij}(t)$ denotes the angle between the direction $\vec{e}_i(t)$ of motion and the direction $-\vec{n_{ij}}(t)$ of the object exerting the repulsive force. See [9].

So we can write pushing work by:

$$W_{push} = \sum_{\forall \text{ person in } \Omega_i} f_{ij}^{push}(t)\Delta s_j \tag{8}$$

Where Ω_i is the set of people in which one of the helper robots have reached the living space, if an individual is at certain distance from the robot, more than two meters, it is considered that the robot does not penetrate in his living space, and therefore is not affected by the drag force.

3) Traversing Work: And last but not least, the *Traversing force* is determined by the forces applied by the robot when is traversing the crowd. For security reasons, we have considered in this research that the value of this force is infinity, so we will ensure that a robot will not cross the crowd in order to avoid any damage.

C. Total Cost for One Robot

The cost function for robot i, given a specific task, is the following one:

$$W_i = \delta_{mot}W_i^{mot} + \delta_{drag}W_i^{drag} + \\ + \delta_{push}W_i^{push} + \delta_{trav}W_i^{trav} \tag{9}$$

$$\text{where } \delta_k = \begin{cases} 1 \text{ if this task is assigned} \\ 0 \text{ if this task is not assigned} \end{cases}$$

Where k could be *pushing, dragging, traversing* or *motion*. For each period of time, the leader and shepherded robots will be given a task in the guiding mission, which will imply one or several robot motion works and human robot works.

D. Optimal Robot Task Assignment

Finally, the task assignment for the robots will be the one which minimizes the minimum assigned work cost required to do the global task. It is computed by the following way:

$$C = argmin\{W_{total}(c)\}, \ \forall \text{ configuration c} \tag{10}$$

where the *Configurations* mean how the tasks are distributed among the robots, for each configuration c robots compute W_{total} which is the addition of all W_i for all robots i that are working cooperatively.

Once we have this cost function, we can determine which are the optimal trajectories the robots must follow to achieve their goal, and which are the roles for each robot. There is

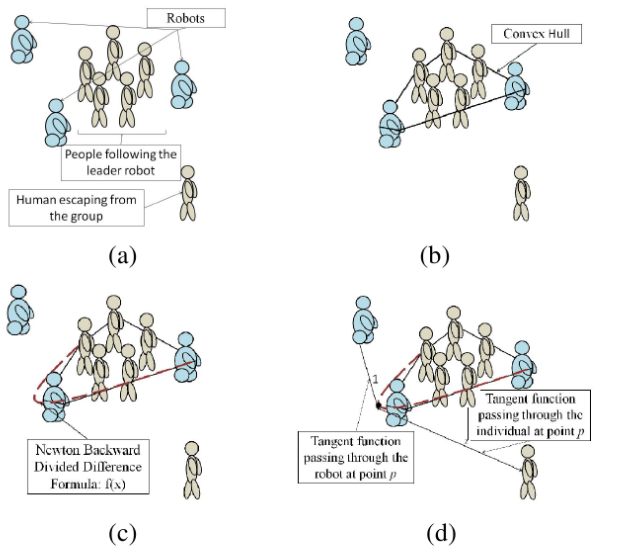

Fig. 1. (a) Environment representation with people and robots. (b) Computation of the convex hull. (c) Interpolation of the convex hull with Newton Backward Divided Difference Formula. (d) Computation of the trajectory for rescuing the individual, this trajectory is composed by two tangents of the function f(x) at point p: (1) passing through the shepherd robot (2) passing through the individual is escaping.

a special case in which several people escape in opposite directions at the same moment, in that situation shepherding robots will go to rescue the individual which has the lower cost function and be redirect to the formation. If the number of people escaping in opposite directions is greater than the number of shepherding robots, robots will act by the same way than previously, and once the robot has redirect the human to the formation, if it is possible, it will search for people who have not been renewed yet.

IV. Computation of Configurations for Group Reunification

One of the most common problems we can find when robots guide a group of people is when one or more people escape from the group, either because they are attractive by an interest point outside the trajectory of the group or because they do not want to continue. The role the robots should follow is trying to rejoin the group that is distancing, as its main objective is to bring everyone in the group to the goal. In this section we proceed to describe the method of reintegration people who are escaping the group through the cost function we have described previously.

When this problem occurs, it is necessary that robots change their goals, for instance, one of the shepherd robot can change its direction, instead of following leader's trajectory, it should rescue people who are distancing the formation, or leader robot can become an assistant one. Therefore, it is necessary to evaluate which is the cost and which are the consequences of such changes of role and trajectories. Below, it proceeds the description of the computation of trajectories using the cost function.

In order to achieve that robots act with sufficient prior need, it is necessary to make a prediction of people's positions and motion vectors [1]. Once the estimated position and direction are obtained, we compute the work cost function, explained before, for each robot, and we will consider the configuration C which minimizes that function, that is:

Once, the configuration with minimal work cost is obtained, the trajectory the robot must follow to regroup people is described as follows: the convex hull of people and robots positions is computed, in this current state the group of people who are escaping in the same direction is regarded as a single element, taking the position as the arithmetic center of the group, see Fig. 1(b). Having reached this point, the function that interpolates the points in the convex hull is computed for each robot using Newton Backward Divided Difference Formula, but only are considered those that are in the area located between the robot is computing the convex hull and the group that is escaping, and by this way we get the function $f(x)$, see Fig. 1(c).

Here, we should compute the trajectory of the robot, it is considered the tangent of $f(x)$ that passes through the center position of the escaping group. This procedure will be given every interval of time k until the robot arrives to the escaping group and it is redirected toward the training that must be followed, see Fig. 1(d).

In the experiments section will present the results of the computation of trajectories according to the cost function and there will be a descriptive and comparative study.

To compute the total work we compare different trajectories and the one that obtain a lower cost function is chosen.

V. Experiments and Results

The current work is done within the framework of the European Project URUS [14], and the scenario where the experiments will be performed corresponds to an urban area of about 10.000 m^2 within the North Campus of the Technical University of Catalonia (UPC), this area contains a network of external cameras which provides information to the robots of human behavior.

The results we will expose correspond to different synthetic experiments. We have considered two scenarios that robots can find in the North Campus of UPC: open areas and cross areas. In these experiments, the dynamical models of the persons, we have considered a group of 9 persons, will follow the models described by Helbing et al. [10]. We will assume a group of three robots, that will move according to the motion model DTM, and acting according the computation of configurations explained in Section III.

We made two different experiments. In the first one, three robots guide a group of nine people in an open area without obstacles see Fig. 2. The position of the three robots is plotted with circles and nine persons are represented by asterisks. As we have explained previously, when robots find new challenges, for instance regrouping people who are escaping, they should analyze which is the optimal trajectory and optimal formation, that is, the analysis of different configurations. Possible configurations for regrouping people with three robots, one leader and two shepherd robots are the following: (i) Robot shepherd 1 takes care of grouping people who have escaped following right path 2. (ii) Robot shepherd

TABLE I

TABLE ON WORK VALUES OF THE DIFFERENT CONFIGURATIONS

Configuration	Open area	Cross area
Conf.1	**42.24**	Inf
Conf.2	152.66	81.44
Conf.3	108.63	**32.04**
Conf.4	113.46	Inf
Conf.5	205.31	130.30
Conf.6	55.03	91.65
Conf.7	72.01	149.79

1 takes care of grouping people who have escaped following left path. (iii) and (iv) Robot shepherd 2 regroups people who have escaped following right and left path respectively. (v) robot leader regroup the formation, the entire group moves toward the escaping people, (vi) and (vii) robot shepherd 1 takes the role of leader while robot leader is moving toward the escaping people, robot shepherd takes the role of leader, respectively. In table 1 we present the values of the optimal robot task assignment function for those configurations. One can notice that configuration 1 has the minimum value and for this reason is the one we have considered, therefore, crowd formation will follow the leader and robot shepherd 1 will recover people who is escaping.

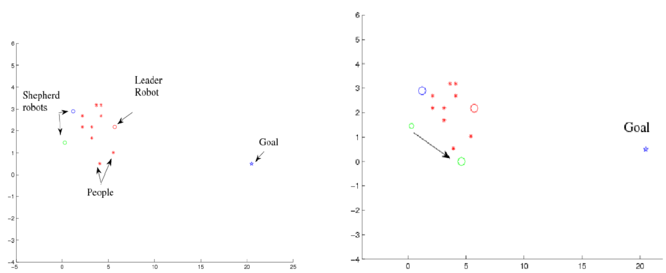

Fig. 2. Experiment 1: Configuration 1. Robot shepherd 1 takes care of grouping people who have escaped following right path.

In the second experiment we introduced a common scenario, a cross area. In the sequences of Fig. 4-10 different time instances are shown, again assuming that one robot needs to follow one of the individuals who left the group. In table 1 there are the results of the cost function for this second experiment, here we can observe that in configurations 1 and 3 this value is infinity, since for obtain the desired configuration robot should move thought the group. One can notice that configuration 3 has the minimum value and for this reason is the one we have considered, therefore, crowd formation will follow the leader and robot shepherd 2 will recover people who is escaping.

Finally, in Fig. 3 (bottom) we present the evolution of the cost function computed using different robots behaviors, it can be seen that the behavior that obtains the lower cost is the one which follows the optimization of the cost function presented previously. In Fig. 3 (top) the trajectory the group has followed is presented. Hence, the cost function minimizes globally the work of the group of robots along all the mission.

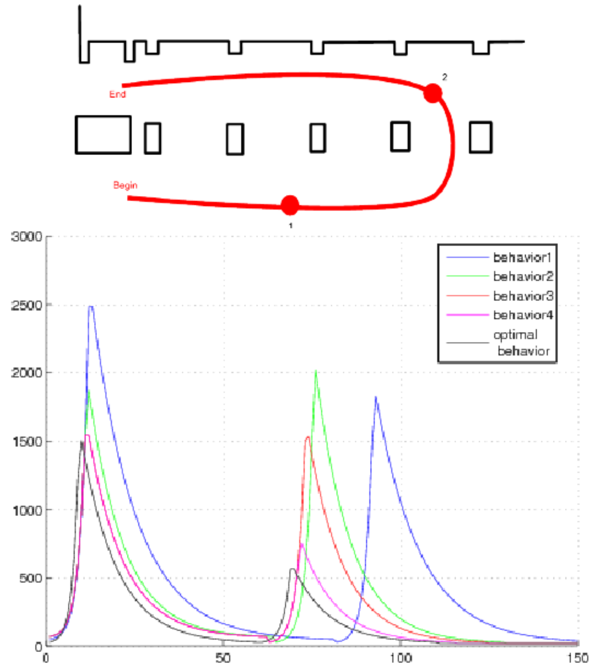

Fig. 3. Top: Trajectory followed by a group of people being guided by three robots, point 1 and 2 are the representation where people have tried to escape. Bottom: Evolution of the cost function along time of different behaviors of robots when people are escaping. Behavior 1: Robot Leader looks for people who are escaping. Behavior 2: Shepherd Robots look for people who are escaping without choosing the shortest way. Behavior 3: Shepherd Robots interchange their positions before looking for people who are escaping. Behavior 4: Shepherd robot which is nearest of people who are escaping is the responsible for resolving this mission without considering the forces presented before. Behavior 5: Robots choose the configuration which minimizes the cost function.

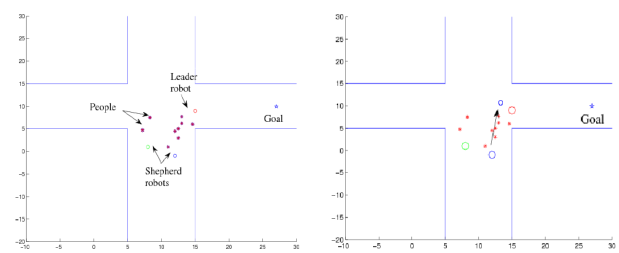

Fig. 4. Experiment 2: Configuration 1. Robot shepherd 1 takes care of grouping people who have escaped following right path.

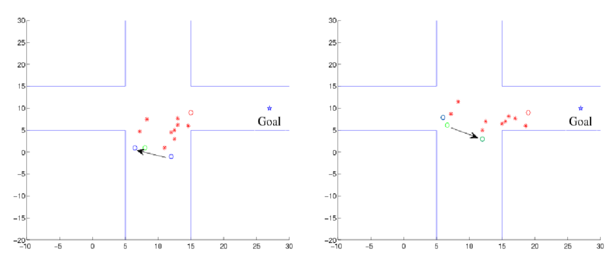

Fig. 5. Experiment 2: Configuration 2. Robot shepherd 1 takes care of grouping people who have escaped following right path.

VI. CONCLUSIONS

We have presented a new cost function for optimizing cooperative robot movements for guiding and regrouping

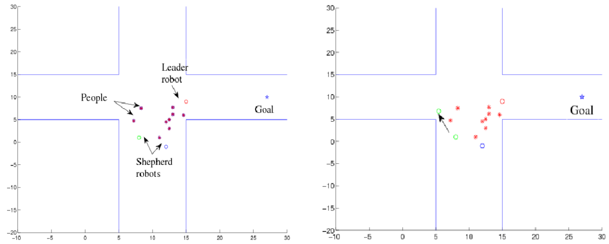

Fig. 6. Experiment 2: Configuration 3. Robot shepherd 2 takes care of grouping people who have escaped following right path.

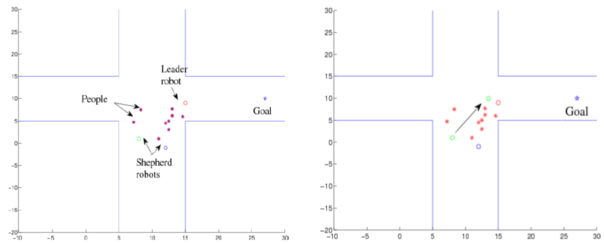

Fig. 7. Experiment 2: Configuration 4. Robot shepherd 2 takes care of grouping people who have escaped following left path. Two different instants of the path are shown (a) and (b).

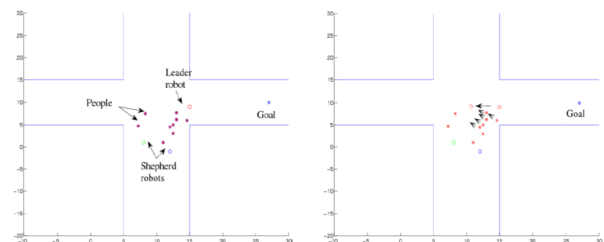

Fig. 8. Experiment 2 Configuration 5. Robot leader regroup the formation, the entire group moves toward the escaping people.

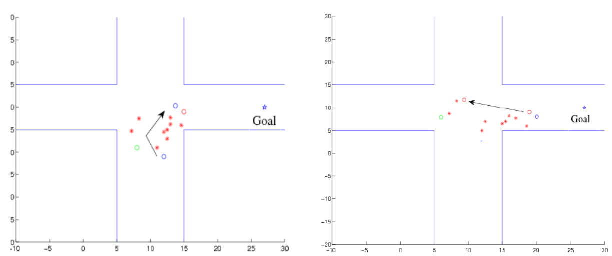

Fig. 9. Experiment 2 Configuration 6. Robot leader regroup the formation, robot shepherd 1 takes the role of leader while robot leader is moving toward the escaping people.

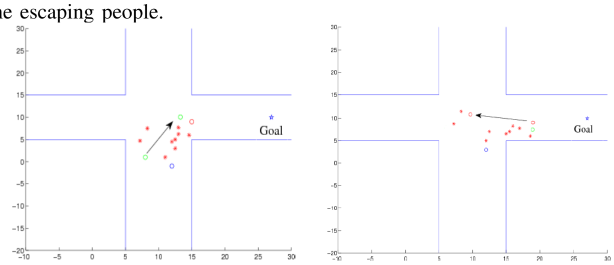

Fig. 10. Experiment 2 Configuration 7. Robot leader regroup the formation, robot shepherd 2 takes the role of leader while robot leader is moving toward the escaping people.

people in guiding missions. In contrast to existing approaches, our method can tackle more realistic situations, such as dealing with large environments with obstacles, or regrouping people who left the group. For that reason, this work can be applied in some real robots applications, for instance, guiding people in emergency areas, or acting as a robot companion.

We presented various results in different situations: guiding in open areas and areas with an obstacle, and can be extended to urban areas with a large number of obstacles. In all of these experiments we showed that the robots can act early enough to satisfactorily guide group of people through a path calculated previously through an exhaustive analysis of different configurations of cooperatively robot motion.

Although our method optimizes locally the cost function, if we are able to know the complete trajectories, then we will be able to compute the global optimal configuration of the robots. This study will be analyzed in future work.

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