

Adaptive Formation Behaviors of Multi-robot for Cooperative Exploration

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Abstract— This paper proposes a method for constituting the formation of a multi-robot system according to dynamically changing environments. First, we apply a method of multi-objective behavior coordination for integrating behavior outputs from the fuzzy control for collision avoidance and target tracing. Second, we apply a spring model to calculate the temporary target position of each robot for the formation behavior. Third, we discuss multi-robot behaviors based on the concept of coupling. The tight coupling is realized by the spring model while the loose coupling is realized by the individual decision making based on connection and disconnection with other robots. Furthermore, the proposed method is applied to the exploration in unknown environments. Finally, we discuss the effectiveness of the proposed method through several simulation results.

Keywords- multi-agent system; formation; exploration; monitoring; fuzzy control;

I. INTRODUCTION

Recently, various types of intelligent multi-agent systems and multiple distributed autonomous robots have been proposed to realize a large size of autonomous systems [1-8]. Multi-agent systems have been applied to various problems such as autonomous guided vehicles, and soccer robots, search and rescue system by multi-robot.

In this paper, we apply multi-agent system to the monitoring and exploring in unknown environments by a multi-robot system. The monitoring and exploration by a multi-robot system are often more effective than that by a single robot with high performance although the performance each robot used in multi-robot system is not high. Since their facing environment changes dynamically every moment, the suitable shape of multi-robot formation also should be changed. Many researches on the multi-robot formation have been conducted until now [9-15]. The methodologies to realize the formation is categorized into two types according to the decision of the robot's position. The first is the method which all robots in the formation uniformly refers to arbitrary reference point to decide its own position. Barfoot [10] proposed the method that allows the multi-robot system to be treated as a single large robot, once configuration of the formation is defined. In this method, each robot decides its own trajectory according to an arbitrary reference point. The second is the method that each robot decides its own position according to the relative position with

other robots. Desai [13] proposed the $l-l$ control and $l-\psi$ control. In the $l-l$ control, robots maintain the distance to two other robots. In the $l-\psi$ control, robots maintain the distance and the angle of another robot. However, the robot can't maintain the formation sometimes. For example, when the robots avoid an obstacle or stop suddenly, the stability of formations is not guaranteed. Fujii [14] proposed the switching control between dynamical approach ($l-\psi$ control) and behavioral approach. In behavior approach, robots choose behavior (turning, wait, and rotate behavior) according to the situation. By this method, the robots are able to adopt themselves to the changing environment with dangerous situations. But, we can realize only simple column formation by this method. If we constitute other shaped formation, we should use other methods.

We propose a method for constituting the formation of a multi-robot system according to dynamically changing environments. First, we apply a method of multi-objective behavior coordination for integrating behavior outputs from the fuzzy control for collision avoidance and target tracing. Furthermore, we apply a spring model to calculate the tentative target position of each robot suitable for the formation behavior. The spring model is a physical model of computing appropriate relative position with other robots connected by virtual springs. By the spring model, we can constitute stable formation when the robots avoid obstacles, or stop suddenly. And, we can constitute a various-shaped formation. We discuss the proposed method from the concepts of loose coupling and tight coupling. The tight coupling is realized by the spring model while the loose coupling is realized by the individual decision making based on connection and disconnection with other robots. For example, each robot coordinates its own position relatively according to the movement of other robots using a spring model in the tight coupling. On the other hand, a robot can be separated from other robots, and can begin to perform the collision avoidance behavior in a dangerous situation. After the robot is safe, the robot can reconnect to other robots in the loose coupling.

This paper is organized as follows. Section II describes a robot in the simulation, its basic intelligent control architecture, the formation behaviors, and multi-objective behavior coordination. Section III shows several simulation results of the formation behaviors of multiple robots. We apply the proposed

method to the exploration in unknown environments. Section IV shows conclusions. We discuss the effectiveness of the proposed method through several simulation results.

II. MULTI-ROBOT FORMATION

A. Multiple robot: MOBiMac

We developed a partner robot; MOBiMac shown in Fig. 1. Two CPUs are used for the interaction with a human and the control of the robotic behaviors. The robot has two servo motors, eight ultrasonic sensors, and a CMOS camera. An ultrasonic sensor can measure the distance to objects. Therefore, the robot can take various actions such as collision avoidance, human tracking, and line tracing. The behavior modes used for this robot are human detection, human communication, behavior learning, and behavioral interaction. The communication with a human is performed by the utterance as the result of voice recognition and human motion recognition. The behavior learning includes the reinforcement learning through interaction with the environment, and imitative learning through interaction with the human. The behavioral interaction includes the soccer and games with a human. Furthermore, a robot in the simulation has LRF (Laser Range Finder) (Fig. 2).

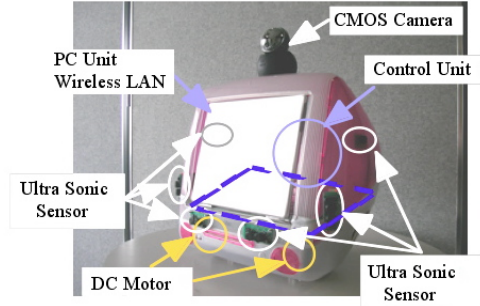


Figure 1. A Partner robot; MOBiMac

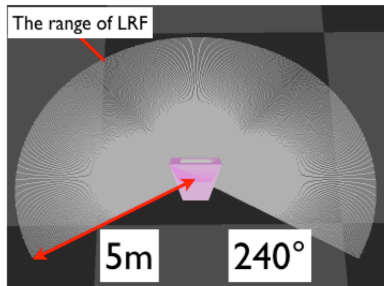


Figure 2. A robot in the simulation

B. Multi-Objective Behavior Coordination

A behavior of the robot can be represented using fuzzy rules based on simplified fuzzy inference [16,17]. The logical structure written by fuzzy rules is easy for humans to understand and to design. In general, a fuzzy if-then rule is described as follows,

If x_1 is $A_{i,1}$ and ... and x_m is $A_{i,m}$
Then y_1 is $w_{i,1}$ and ... and y_n is $w_{i,n}$

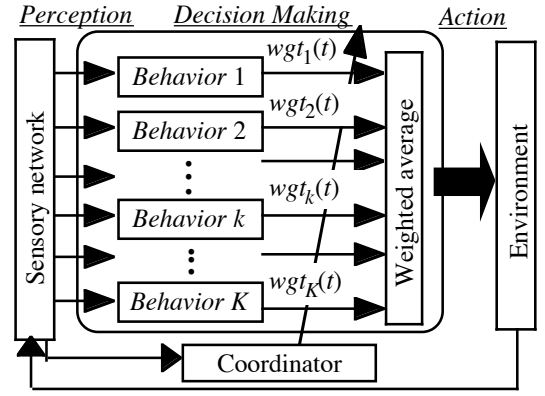


Figure 3. Multi-Objective Behavior Coordination

where $A_{i,j}$ and $w_{i,k}$ are a Gaussian membership function for the j th input and a singleton for the k th output of the i th rule; m and n are the numbers of inputs and outputs, respectively. Fuzzy inference is described by,

$$\mu_{A_{i,j}}(x_j) = \exp\left(-\frac{(x_j - a_{i,j})^2}{b_{i,j}^2}\right) \quad (1)$$

$$\mu_i = \prod_{j=1}^m \mu_{A_{i,j}}(x_j) \quad (2)$$

$$y_k = \frac{\sum_{i=1}^R \mu_i w_{i,k}}{\sum_{i=1}^R \mu_i} \quad (3)$$

where $a_{i,j}$ and $b_{i,j}$ are the central value and the width of the membership function $A_{i,j}$; R is the number of rules. Outputs of the robot are motor output levels. Fuzzy controller is used for collision avoidance and target tracing behaviors. The inputs to the fuzzy controller for collision avoidance and target tracing are the measured distance to the obstacle by LRF, and the relative direction and to a target point, respectively. Basically, a target point is generated by using the objects on the image.

In general, a mobile robot has a set of behaviors for achieving various objectives, and must integrate these behaviors according to the environmental conditions. Therefore, we proposed the method for multi-objective behavior coordination [18] (Fig. 3). This method is composed of a behavior coordinator and a behavior weight updater. A behavior weight is assigned to each behavior. Based on (3), the output is calculated by

$$y_k = \frac{\sum_{j=1}^K wgt_j(t) \cdot y_{j,k}}{\sum_{j=1}^K wgt_j(t)} \quad (4)$$

where K is the number of behaviors; $wgt_k(t)$ is a behavior weight of the k th behavior over the discrete time step t . By updating the behavior weights, the robot can take a multi-objective behavior according to the time series of perceptual information. The update amount of each behavior is calculated as follows,

$$\begin{bmatrix} \Delta wgt_1 \\ \Delta wgt_2 \\ \vdots \\ \Delta wgt_K \end{bmatrix} = \begin{bmatrix} dw_{1,1} & dw_{1,2} & \cdots & dw_{1,M} \\ dw_{2,1} & & & \\ \vdots & & \ddots & \vdots \\ dw_{K,1} & & \cdots & dw_{K,M} \end{bmatrix} \begin{bmatrix} si_1 \\ si_2 \\ \vdots \\ si_M \end{bmatrix} \quad (5)$$

where Δwgt_k is the update rule of $wgt_k(t)$; si_m is the parameter on the m th perceptual information; M is the number of perceptual inputs; $dw_{k,m}$ is the parameter which presents influence of si_m on behavior K . This method can be considered as a mixture of experts if the behavior coordinator is considered as a gating network.

C. A Spring Model for Intelligent Formation behavior

We apply a mass-spring-damper model (we use “spring model” for the abbreviation in this paper) [19] for the control of the multiple robots from the global point of view. Multi-objective behavior coordination integrates the outputs of target tracing, collision avoidance, and the spring model. We call a target position of each robot based on the spring model the temporary target point. The temporary target position is calculated by the 4th-order Runge-Kutta method. We define the angle matrix as

$$\theta = \begin{pmatrix} 0 & \theta_{1,2} & \cdots & \theta_{1,n} \\ \theta_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & \theta_{n-1,n} \\ \theta_{n,1} & \cdots & \theta_{n,n-1} & 0 \end{pmatrix} \quad (6)$$

where the angle is represented as $\theta_{i,j}$ ($i \neq j$, $i, j = 1, 2, \dots, n$) between the x axis and the line connecting between the i th and j th robots (Fig. 4); $\theta_{i,j} = \theta_{j,i} + \pi$. We assume two robots are connected with each other by the virtual spring, the displacement from the virtual free length is defined by $l_{i,j}$ ($i \neq j$, $i, j = 1, 2, \dots, n$), and the displacement matrix is defined as

$$L = \begin{pmatrix} 0 & l_{1,2} & \cdots & l_{1,n} \\ l_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & l_{n-1,n} \\ l_{n,1} & \cdots & l_{n,n-1} & 0 \end{pmatrix} \quad (7)$$

where their connection is asymmetric ($l_{i,j} \neq l_{j,i}$) because the free length is not same in i th and j th robot. The virtual spring constant is defined as

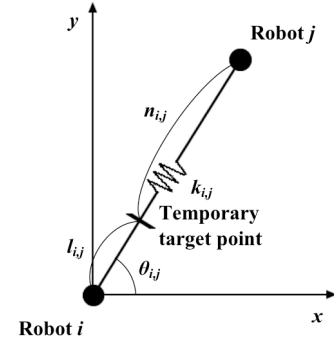


Figure 4. A spring model of two robots

$$K = \begin{pmatrix} 0 & k_{1,2} & \cdots & k_{1,n} \\ k_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & k_{n-1,n} \\ k_{n,1} & \cdots & k_{n,n-1} & 0 \end{pmatrix} \quad (8)$$

The acceleration of the i th robot's temporary target point is defined as the summation of the acceleration based on the spring between the i th and other robots.

$$\ddot{p}_r = -\sum_{j=1}^n \ddot{p}_{r,j} - C \cdot \dot{p}_r$$

$$\ddot{p}_{i,j} = \{d_{i,j}k_{i,j}l_{i,j}\cos\theta_{i,j}, d_{i,j}k_{i,j}l_{i,j}\sin\theta_{i,j}\} \quad (10)$$

$$D = \begin{pmatrix} 0 & d_{1,2} & \cdots & d_{1,n} \\ d_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & d_{n-1,n} \\ d_{n,1} & \cdots & d_{n,n-1} & 0 \end{pmatrix} \quad (11)$$

where \ddot{p} and \dot{p} are the acceleration and velocity; C is the virtual damping constant; $d_{i,j}$ ($=\{0,1\}$) is the connectivity between the i th and j th robots, and the virtual spring connectivity is asymmetric; and mass is assumed as 1 in order to simplify the problem.

D. A Directional Spring Model

This subsection explains the detail of a directional spring model. We assume each robot can know the moving direction of the connecting robot, and can calculate the relative position of the target point based on the directional spring. In Fig. 5, all of points on the circle become locally stable points based on the spring model. Here we use the temporary target point on the circle in order to organize the formation with keeping relative angle $\phi_{i,j}$ with the connecting robot. The relative angle is defined as

$$\Phi = \begin{pmatrix} \mathbf{0} & \varphi_{1,2} & \cdots & \varphi_{1,n} \\ \varphi_{2,1} & \ddots & & \vdots \\ \vdots & & \ddots & \varphi_{n-1,n} \\ \varphi_{n,1} & \cdots & \varphi_{n,n-1} & \mathbf{0} \end{pmatrix} \quad (12)$$

The robots moves toward the temporary target point by using a virtual spring from the temporary target point in order to simplify the problem. Therefore, the equation (10) is rewritten into

$$\ddot{p}_{i,j} = \{d_{i,j}k_{i,j}l_{i,j}^* \cos \theta_{i,j}^*, d_{i,j}k_{i,j}l_{i,j}^* \sin \theta_{i,j}^*\} \quad (10')$$

where $l_{i,j}^*$ is the displacement from the temporary target point; $\theta_{i,j}^*$ is the angle between the temporary target point and x axis. Furthermore, we assume each robot position can be measured by the equipped sensors or received through the wireless communication. By using this calculation model, the robot can organize the formation with keeping the directionality to the connecting robot.

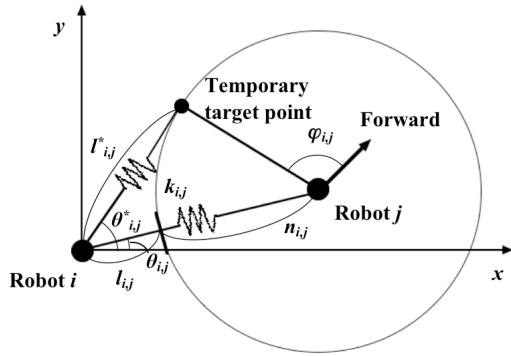


Figure 5. A directional spring model of two robots

E. Formation Behaviors of Multi-robot

Fig. 6 shows the behavior of collision avoidance. The robot avoids a object which the LRF sensed in the short range less than 1 meter. Fig. 7 shows behavior of target trace for monitoring. The robot approaches the a object which the LRF sensed in the long range less than 5 meters. Fig. 8 shows the behavior of temporary target trace. Robot A is connected with robot B and robot C by virtual springs. Robot A move to convergence point of two springs to maintain the defined formation. We unify these three behaviors using multi-objective behavior coordination and constitute intelligent formation (Fig. 9). The relation between a robot and another robot is tight coupling. The formation realize efficient exploration and low burden according to tight coupling. This formation behavior is composed by a leader and multiple followers. The leader is a robot which doesn't communicate with other robots. The follower is a robot which communicate with leader or other followers.

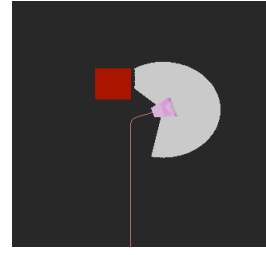


Figure 6. Collision avoidance

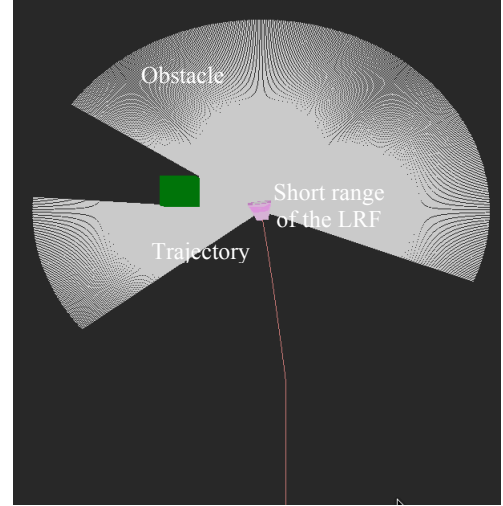


Figure 7. Target trace

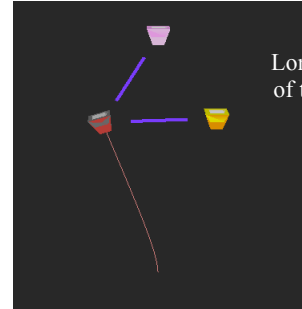


Figure 8. Temporary target trace

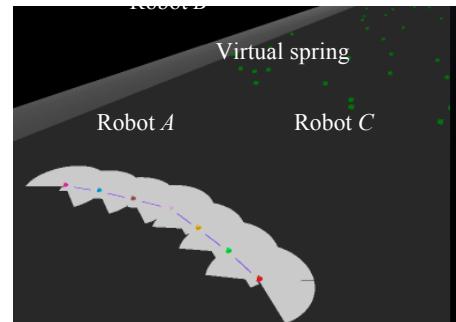


Figure 9. Formation Behavior

F. A reconnection method

The robots in the formation can disconnect and reconnect the virtual springs if needed [20]. For example, a robot cannot reach its temporary target point calculated by the spring model because of obstacles (Fig. 10(a)) or another robot (Fig. 10(b)). If the virtual spring is disconnected, the relation between a robot and another robot is loose coupling. Problems are often solved by loose coupling. In this paper, we use the disconnection and reconnection of the virtual springs for maintaining the range of exploration in the environment which obstacles or targets are located.

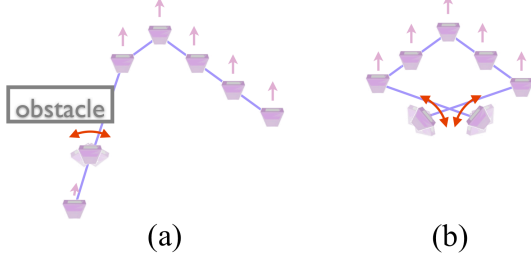


Figure 10. Situation which disconnection is needed

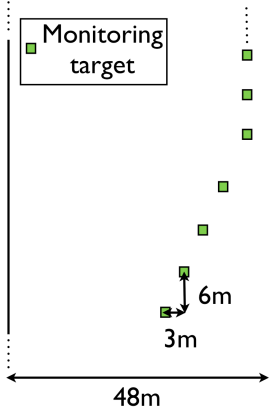


Figure 11. Simulation environment

III. SIMULATION RESULTS

This section shows several simulation results of formation behaviors. This formation behavior is composed by a leader and multiple followers. This spring connection is described as follows.

$$D = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \quad (13)$$

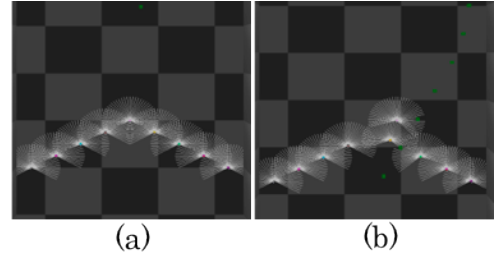


Figure 12. Result 1: No virtual springs

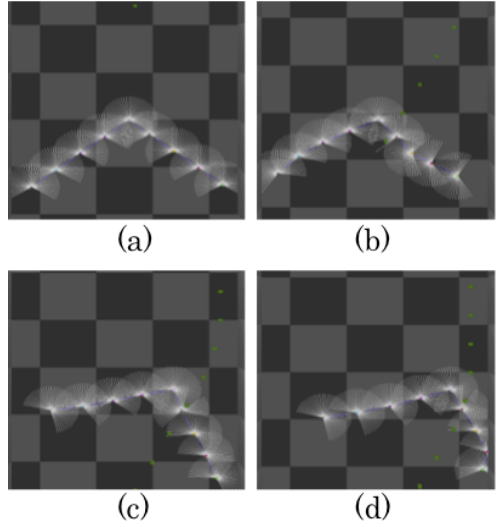


Figure 13. Result2: Triangular formation

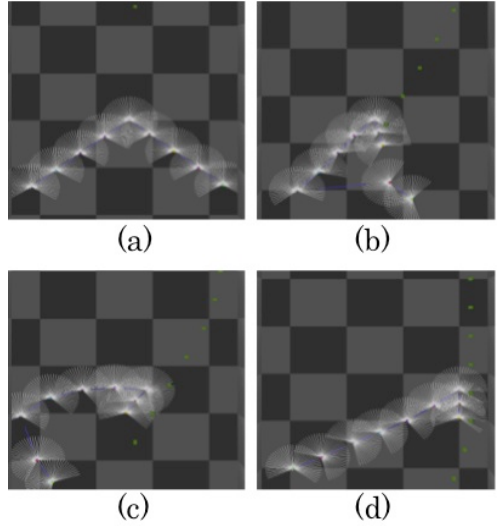


Figure 14. Result3: Reconnection formation

where the number of robots is 9. $l_{ij} = 5$ [m], $k_{ij} = 500$ [N/m], $C = 300$ [N·s/m], and relative angle is given by (14).

$$\varphi_{i,j} = \begin{cases} \frac{2\pi}{3} & (i = 1, 3, 5, 7) \\ \frac{4\pi}{3} & (i = 2, 4, 6, 8) \end{cases} \quad (14)$$

There are some targets which distributed robot should immediately discover and precisely monitor, for example, victim in disaster sites or object in unknown environments. We call it "monitoring target". Fig. 11 shows the environment where monitoring targets gathers on the right side. Fig. 12-14 is simulation results of the formation of 9 robot in the environment shown in Fig. 11. The robots advance to the depth direction in addition to rules decided in Section II D. It is desirable to take behavior which the robots approach the monitoring target, with the exploration range as the formation maintained. In result 1 (Fig. 12), all robots don't communicate with other robots. Even if robots were initially located as the shape of the triangular formation (Fig. 12(a)), some robots approached monitoring targets and gather on the right side (Fig. 12(b),(c),(d)) because they didn't cooperate. In result 2 (Fig. 13), robots constitute the triangular formation. They are able to maintain exploration range initially (Fig. 13(a)). But, the leader robot approach the right side, and so all robots gather on the right side, (Fig. 13(b),(c)). As a result the formation cannot explore left side of the environment (Fig. 13(d)). In result 3 (Fig. 14), the robots which are located in rear right side disconnect the virtual springs with front robot when a monitoring target is discovered by LRF of leader robot (Fig. 14(b)). Then the robots reconnect with a robot in the left bottom (Fig. 14(c)). As a result, the reconnection formation can explore from the left side to the right side of environment including the zone which is not explored in result 2 (Fig. 14(d)). In this way, multi-robot formation realize efficient exploration by making the virtual springs connectivity to use the spring model.

IV. CONCLUSIONS

In this paper, we proposed a method of the constitution of the multi-robot formation and a method of efficient exploration in the dynamic environment. Specifically, we unified plural behaviors such as collision avoidance by the fuzzy control and the suitable target position trace by the spring model, to constitute intelligent formation. We discussed the proposed method from the concepts of loose coupling and tight coupling. We realized the tight coupling by the spring model and realized the loose coupling by the individual decision making based on connection and disconnection with other robots. The simulation results show that the proposed method can solve the problem of gathering of exploration range of multiple robots.

As future works, we apply the reconnection formation to the efficient exploration in complex environment and rescue by multiple robots in disaster sites, and we intend to develop the

reconnection method to be able to let formation adapt to dynamic environment.

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