Paper:

The Behavior Design of Swarm Robots based on a Simplified Gene Regulatory Network in Communication-free Environments

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Abstract. Aiming at the problem of frequent failure of swarm robots encirclement strategy in the battlefield environment without communication and unknown environment, this paper proposes a model named S-GRN (Simplified Gene Regulation Network) based on individual cognition, which make swarm robots track and entrap targets in communication-free environments. FSM (Finite-State Machine) model is designed to guide the behavior mode of robot and achieve effective control of swarm robot. Based on the above ideas, the behavior mode of swarm robots in communication-free environments and the emergence method of swarm aggregation form are designed. This method is a distributed control method. Swarm robots recognize the approximate orientation of targets through their own visual sensors, and measure the orientation of obstacles with laser sensors. These information are used as the inputs of S-GRN, then output is target entrapping pattern. Through the control algorithm based on FSM, each robot moves to the target and reaches the pattern point around the target. Finally, as the robot gathers towards the target, cluster tracking and encirclement forms emerge. The effectiveness of this method is verified by experiments.

Keywords: Swarm Robots, Communication-free Environments, Simplified Gene Regulatory Network, Finite-State Machine

1. INTRODUCTION

Nowadays, more and more researchers pay attention to swarm robot system because of its wide application, such as coordinated patrol[1][2], task allocation [3][4], target tracking and navigation [5][6], autonomous search and rescue[7], etc. In these studies, the surround control of swarm robot system has attracted the interest of many researchers because of its practical value in civil and military fields. Its application scope includes reconnaissance and surveillance using robot clusters with multiple sensors[8][9], capturing enemy targets using multiple UAVs[10], and protecting targets by a team of armed robotic vehicles (ARVs) [11]. The main problem of the above application is to control a group of intelligent unmanned platforms to form the expected formation, entrap specific targets, and finally form a circle.

The mainstream researches on target entrapping by swarm robots are as follow. In the existing literature on this problem, the method based on graph theory and classical control theory is favored by most researchers [12][13][14][15], because the topology of robot connection can be accurately described by graph. However, it has an obvious limitation that it is very dependent on accurate physical mode, which is usually difficult to obtain in practice. The representative work is as follows: Yamaguchi [16] designed a feedback control law to control the swarm robots to form an encirclement formation for the target. In order to enable robots to form a round-up formation and avoid collision independently, Liang et al. [17] designed a round-up method based on artificial physical force. The target attracts the robot and other companions repel the robot. Under the action of artificial force, the robot crowd completes the round-up; Huang et al. [18] established loose preference based motion rules to promote individuals to independently choose the correct path to form a round-up formation in which companions maintain a certain distance to avoid collision; Zhang et al. [19][20][21] proposed obstacle avoidance and target entrap methods based on simplified virtual force model, so that swarm robots can maintain a formation that takes into account both encirclement and obstacle avoidance in unknown and complex environments. Ru et al. [22] considered the actual factors like target information and robot-to-robot communication, and used the multi hypothesis tracking method to obtain the estimation of target position and speed from the complex environment, and then designed the control algorithm based on the system consensus theory and multi-agent communication topology to form and maintain the formation to entrap the dynamic target. In the case of multi-objective, Chen et al. [23] combined Glasius heuristic neural network and confidence function to carry out path planning for hunting robot, and proposed a time competition mechanism for establishing dynamic hunting alliance to finish multi-objective task allocation. In addition, Cao et al. [24] proposed that search a state transition model composed of three states of obstacle avoidance and encirclement completes the encirclement task through the transition between states under different conditions.

However, these models all have shortcomings. Yamaguchi's method [16] needs to always determine the relationship between robots as a strong connection graph, that is, the formation order of swarm robots is fixed, which can ensure the stability of formation. But this method reduce the flexibility and robustness of swarm robots in carrying out entrapping task. The entrapping method based on artificial physical force [17] by Liang Zeng et al. and the entrapping method based on simplified virtual force model [19][20][21] by Zhang et al., both have no restrictions on the perception range of robot individuals. In addition, individual obstacle avoidance is not considered in the entrapping method based on artificial physical force [17] by Liang Zeng et al. The model based on loose preference rules [18] of Huang et al., and the joint tracking and search algorithm [22] of Ru et al. Zhang's obstacle avoidance method based on the simplified virtual force model [19-21] is to give the corresponding forward deflection angle after judging that the obstacle is non-convex or convex. So, the agent can continue to move after rotating at the desired angle in situ, and the obstacle avoidance efficiency is not high. The path planning method adopted by Chen et al. [23] requires map information to establish a grid map, and selects the point with the maximum network activation value as the next target. Cao's state transition model [24] relies on a large number of evenly arranged sensors on the individual to determine the direction of the target or companion.

The above models can not completely solve the problems of limited individual perception range, no obstacle avoidance ability or low obstacle avoidance efficiency, unknown map information and unable to use centralized controller. In addition, different from daily life application scenarios, swarm robots are often used in communication-free environments, such as battlefield and disaster scene. Under the condition of no communication, the communication between robots and command center or between robots is disturbed, which can't ensure high-speed and reliable communication or data transmission. Therefore, it is difficult for swarm robots to complete the target search task through the real-time control of the commander. Each robot needs to have the ability to complete the task independently and intelligently without command, and realize the autonomous cooperation between swarm robots as much as possible.

The main contributions of this paper are summarized as follows: 1) A S-GRN (Simplified Gene Regulation Network) model is proposed to make swarm robots adapt to the communication-free environments. It only needs to input visual information and distance information. So as to reduce the computational burden and ensure that swarm robots can track and entrap the target successfully; 2) The behavior of robots are decomposed and abstracted into a variety of states. Then we design a FSM model to guide the behavior mode of each robot, which not only make the swarm robots approach the target, but also avoid the neighbor robots and obstacles. 3) We use E-puck2 robot to do some real-world experiments. The experimental results verify the effectiveness and feasibility of the proposed model in communication-free environments.

2. Entrapping Pattern Generation

2.1. Entire Framework

The proposed scheme in this paper is shown in Fig. 1, S_0 indicates the environments information perceived by the robots at the current time. Then S_0 is entered into S-GRN model to generate the concentration field and the target entrapping pattern which consists of many pattern points. We input these pattern points into the robot's controller, and generates control command to the actuator on the robot to make the robots constantly approach the pattern points and avoid obstacles at the same time. While the robot is running, the camera and laser sensors are used to attach to the robots, obtain the position information of the target and obstacles in real time, then this information is input into the S-GRN model again to update concentration field information and create new pattern point. After that, the controller generates new control instructions to guide the robots to move to the continuously updated pattern points until the robots entrap the target, then achieve the effect of target tracking and entrapping.

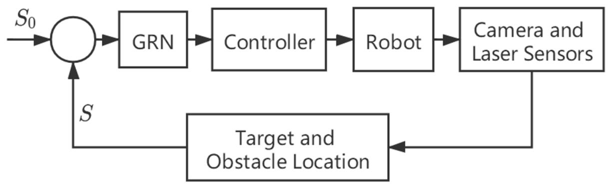

Fig. 1. Visual robot scheme based on simplified gene regulatory network

2.2. Target Detection and Environment Perception

In the communication-free environments, it is difficult for robots to obtain the global position information. Therefore, each robot needs to perceive the environment through its own camera and laser sensors, detect the surrounding targets and obstacles, obtain their position information, and establish its own coordinate system.

As shown in Fig. 2, the establishment method of robot individual local coordinate system is as follows:Taking robot itself as the coordinate origin, taking the camera orientation as the y-axis, and the y-axis rotates 90 degrees clockwise as the x-axis. The distance d and angle θ between the target and robot itself can be obtained through its camera and laser sensors. The position coordinates (x_i, y_i) of target A in the robot coordinate system

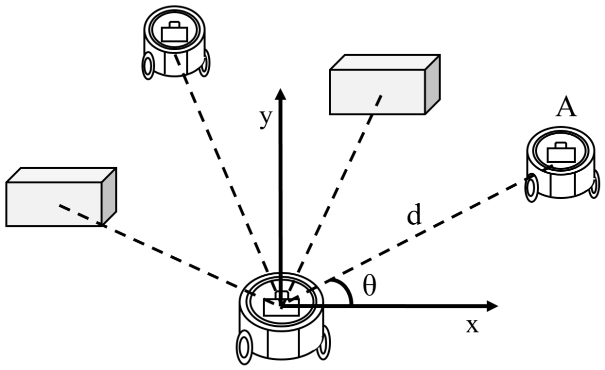

Fig. 2. The schematic of robot Coordinate system

are obtained through trigonometric function transformation. After that, it is necessary to input the coordinates of all surrounding targets and obstacles into the S-GRN to generate the concentration field and target entrapping pattern.

2.3. Gene Regulatory Network

GRN (Gene Regulatory Network) refers to the network formed by the interaction between genes in cells (or in a specific genome). Among many interaction relationships, GRN also refers to the interaction between genes based on gene regulation. GRN is the mechanism of controlling gene expression in organisms. When genes are expressed, mRNA stored in the genome is transcribed and translated into proteins. Some of these proteins (such as transcription factors) can regulate themselves or the expression of other genes. Therefore, protein production is regulated and controlled by genes, which forms a complex interactive gene network. The diffusion of proteins generates a concentration field that in turn activates or inhibits the expression of other genes. Inspired by this biological mechanism, we designed a swarm robots control scheme based on GRN.

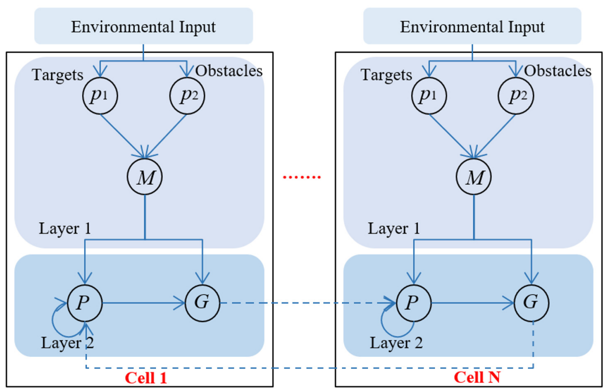

Fig. 3. A diagram of the simplified gene regulatory network

As shown in Fig. 3, the proposed S-GRN in this paper is a structure that suitable for communication-free environments. S-GRN is divided into upper layer and lower layer. In the upper layer, p_1 and p_2 are proteins which can be regulated by environmental inputs. Protein M is a fusion gradient describing the pattern to be formed, which can influence the production of both proteins P and G.

Next, we analyze the scheme in detail. Firstly, based on the position of the detected target, the target form will be generated by the gene regulation function in the first layer. The adaptive population morphology generation process includes two steps: 1) The morphological gradient space is formed according to the gene regulation function; 2) The equipotential line that gradient value is greater than the threshold is extracted as the generated group form.

In the process of target pattern generation, the robot that detects the target will generate the morphological gradient space about the target through (5) and (6). In equations (1) to (6), γ_i and β_j are scalar values, which are expressed as target and obstacle inputs respectively. Where i represents the i^{th} target and j represents the j^{th} obstacle. It is worth noting that, γ_i and β_j is a constant positive number at the position of the target and obstacle respectively, and other positions are zero (the position without target and obstacle is zero).

$$\frac{dT_i}{t} = \bigtriangledown^2 T_i + \gamma_i - T_i \tag{1}$$

$$\frac{dO_j}{t} = \bigtriangledown^2 O_j + \beta_j - j \tag{2}$$

$$T = \sum_{i=1}^{N_t} T_i \tag{3}$$

$$O = \sum_{j=1}^{N_o} O_j \tag{4}$$

$$\frac{dM}{dt} = -M + sig(1 - T * T, \theta, k) + sig(O * O, \theta, k) \tag{5}$$

$$sig(x, \theta, k) = \frac{1}{1 + e^{-k(x-\theta)}} \tag{6}$$

Where T_i represents the protein concentration formed by the i^{th} target in the environment (γ_i, target position information), O_j represents the Protein concentration formed by the j^{th} obstacle in the environment (β_j, obstacle position information). T and O are the combined concentration produced by all targets and obstacles, respectively. $\bigtriangledown^2$ is a Laplace operator which is defined as the second derivative of T_i and O_j in the morphological gradient space, and regarded as the process of protein diffusion in biological system. M is defined as the morphological gradient space formed by the target and obstacle. It should be noted that when there is no obstacle around the target, equation (5) will be simplified to (7).

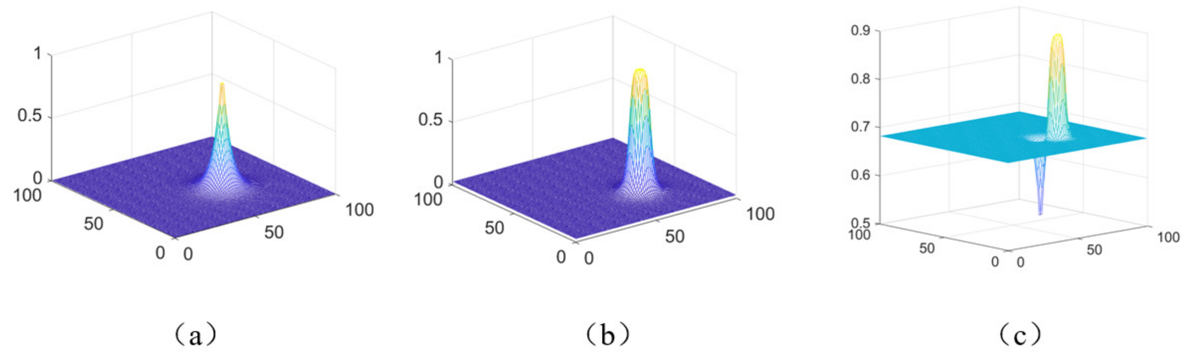

Fig. 4. Morphological concentration space diagram. (a) is the morphological concentration space formed by target, (b) is the morphological concentration space formed by obstacle, and (c) is the comprehensive morphological concentration space.

$$\frac{dM}{dt} = -M + sig(1 - T * T, \theta, k) \qquad (7)$$

Where θ and K are regulation parameters.

Then, how do M form morphological gradient space based on target and obstacle information? Suppose that there is only one target in the environment and only one obstacle around the target, firstly, constant γ and β are entered at the position of the target and the obstacle respectively. Then, the protein concentration fields establish by T and O, and decay as the distance from the target and obstacle increases, as shown in Fig. 4 (a) and (b). In particular, through (5), the concentration field formed by the target and the obstacle can be in the opposite states, that's to say, the closer to the target, the lower the concentration, and the closer to the obstacle, the higher the concentration, as shown in Fig. 4 (c).

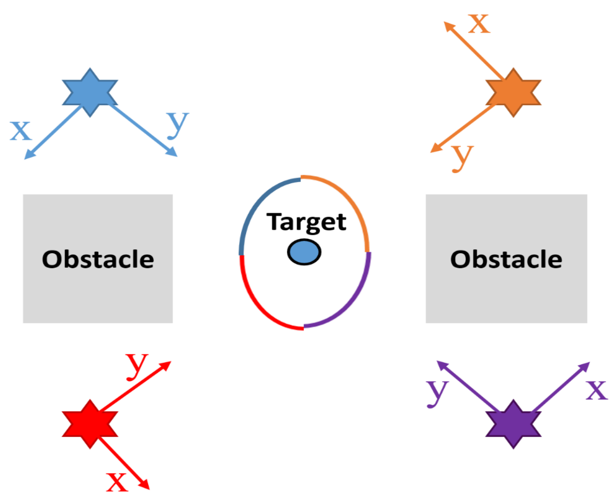

Fig. 5. Target entrapping pattern.

After generating the concentration space, we take the points with the same concentration as the pattern points to generate the target entrapping form. As shown in Fig. 5, the local entrapping forms generated by multiple robots can be superimposed to form a complete target entrapping form.

3. The Behavior Design of Swarm Robots

FSM (Finite-State Machine) is a behavior modeling tool for object. Its function is mainly to describe the state sequence experienced by an object in its life cycle and how to respond to various events from the outside world.

We found the following problems when designing the behavior of swarm robots: 1) How do swarm robots make relatively reasonable behavior in complex environment? 2) In the dynamic and real-time environment, swarm robots how to track the target without collision with the neighbor robot?

To solve these two problems, we use FSM to design the behavior mode of swarm robot. Firstly, the entrapping behavior of robot is decomposed into several parts: searching for the target, discovering the target, generating the target hunting form, moving to the hunting point according to the concentration gradient, obstacle avoidance and so on. And then abstraction into several states, including freedom walk, search target, calculating pattern, close to target, far away from target, robot on pattern, and so on. Finally, the event triggered state transition is designed, that is, the trigger condition is designed. Therefore, we design a FSM model to guide the behavior mode of each robot, which makes the swarm robot better approach the target and avoid obstacles at the same time.

As shown in Fig. 6, the inputs of FSM are the data from camera and laser sensors. The states of robot are divided into 8 kinds. Trigger events causing state transition include whether the camera can recognize the target, whether the distance measured by laser sensor reach the preset threshold, whether the time reaches the time threshold, or whether the mobile distance of the robot reaches the threshold. The robot will remain in one state until an event triggers it to change to another state.

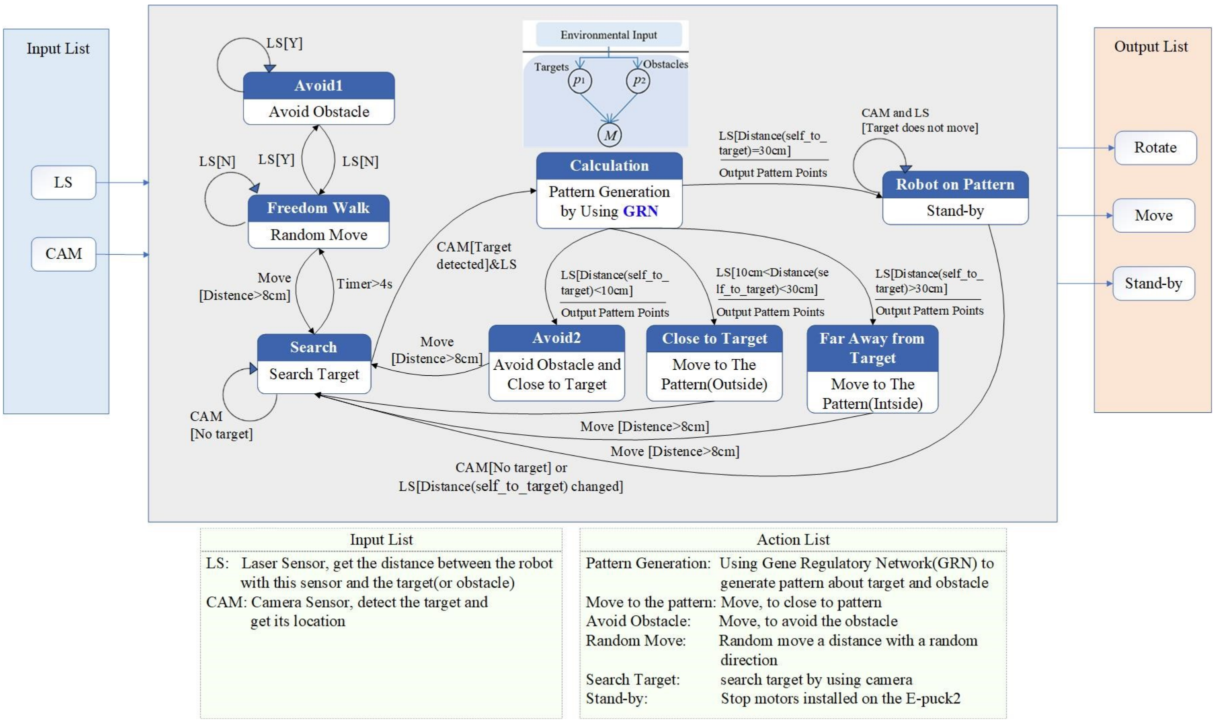

Fig. 6. The finite-state machine of swarm robots

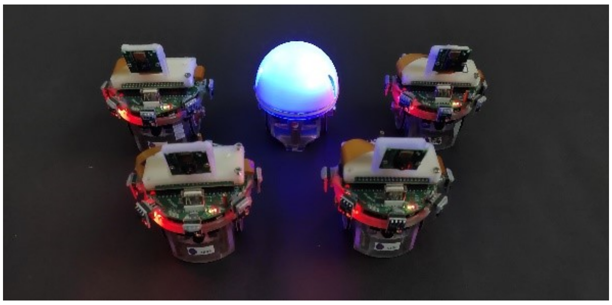

Fig. 7. Experiment platform: E-puck2.

4. Experiment and Analysis

In order to verify the effectiveness of swarm robots approach we proposed, we use E-puck2 as our experiment platform, which shown in Fig. 7. We add an expansion board on e-puck2, and equip with raspberry pi zero w, camera, and five laser sensors (the placement angle is 0 °, ± 45 °, ± 90 ° with the y-axis of the robot coordinate system). The experiment sets that the targets has characteristics of blue light.

4.1. Experimental Scenarios and Metrics

In order to verify the environmental adaptability of the algorithm, we set up two experimental scenes on a 3m * 3m site, and randomly arrange obstacles in the scenes. In order to verify the performance of S-GRN model in target entrapment and tracking, we design three evaluation indexes: swarm robots aggregation shape transformation ability, swarm robots entrapping ability, and swarm robots fault tolerance ability. 1) Swarm aggregation shape transformation ability: During the process of tracking or entrapping the target, the target entrapping shape can change with the change of the environment. At the same time, the group aggregation shape transformation time $T < 100N$ seconds (n is the number of group robots); 2) Swarm robots entrapment ability: When the entrapping swarm robot are located in the target entrapping pattern (whether entrapping is successful or not, as shown in Fig. 8, E-puck2 platform r = 40cm). When the number of targets is M and the number of the swarm robots is N (E-puck2 platform: N ¿ = 3M, N ¡ = 20), the number of successfully entrapping targets needs to account for more than or equal to 80% of the total targets. 3) Swarm robots fault tolerance ability: whenever robot breaks down, other robots can still track and entrap target. The scale of swarm robots is N, the number of robot failures is a, we need $a < 0.2N$ during the experiment.

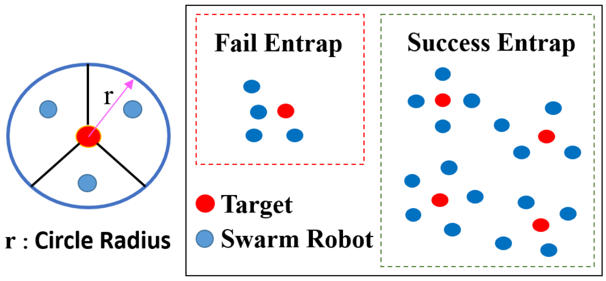

Fig. 8. Entrapping target diagram

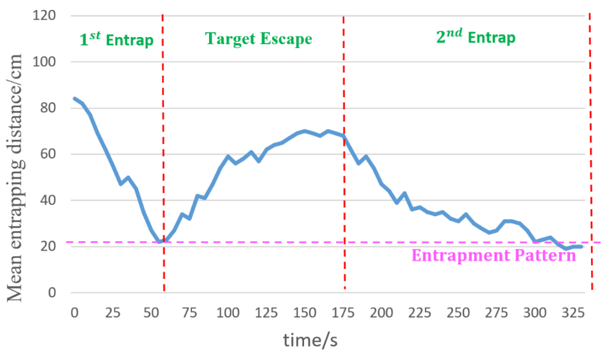

Fig. 9. The average entrapping distance of swarm robots

4.2. Swarm Robots Experimental

The experimental steps of swarm robots are as follow: Firstly, the swarm robots are distributed in a rectangular shape. Then, the robot who uses the algorithm proposed in this paper moves to the target and entraps the static target for the first time; Then the target begins to escape. Swarm robots follow it, and updates the tracking and entrapping pattern in real time with the change of environment, so as to realize entrapping dynamic target the second time. All experiments are carried out in communication-free s. The swarm robots only get the position of obstacles and targets through its own sensors.

Fig. 10 shows the experimental process of typical scene 1. In the experiment, the obstacles were placed in the shape of a narrow passage. Six E-puck2 robots track and entrap one target. We can analyze the experiment in combination with Fig. 9. The first task is to entrap static target, and the swarm robots are transformed from rectangular shape to entrapping shape. Then, the target starts to escape to the narrow road and pass through it. The swarm robots track the target. When passing through the narrow road, in order to adapt to the environmental changes, swarm robots change to the shape of water drop. After passing through the narrow road, the target stops, and the swarm robot realizes the secondary surrounding of the target. As shown in Table.1, the average group aggregation shape transformation time is 105s, which is far less than 600s required by the index. The success rate of entrapment is 100%. There is almost no robot breaking down, which meets the requirements of the index.

Fig. 11 shows the experimental process of typical scene 2, in which obstacles are placed randomly. Two targets are tracked and entrapped by 20 E-puck2 robots. Like scene 1, swarm robots also successfully complete tracking and entrapping tasks. During this process, there are robots breaking down, but the entrapping effect is not affected. As shown in table.1, the average swarm aggregation shape transformation time is 150s, which is far less than 2000s required by the index. The success rate of entrapment is 100% and the robot failure rate is 5%, which meets the requirements of the index.

Through experiments, we can see that in communication-free environment, swarm robots based on S-GRN can track and entrap static or dynamic targets. In the process, it can also adapt to the changes of environment in real time without collision with obstacles. The experimental results meet the index requirements.

5. Conclusion

In this paper, S-GRN model based on individual cognition is proposed as an entrapping method for swarm robots. This method can adapt to communication-free environment, like battlefield. On the one hand, according to the information obtained from the environment, swarm robots establish entrapping pattern of the target through GRN model. On the other hand, swarm robots follow FSM model that guides their behavior patterns, and moves towards the target while avoiding obstacles. Finally, as the robots gather towards the target, the form of entrapping emerges. The biggest advantage of this method is that in communication-free environments, swarm robots do not need to communicate directly with each other to emerge the form of encirclement, but emerge the form of tracking and entrapping through the indirect communication through camera and laser sensors. Then, it is verified by real machine experiments that the proposed method can automatically adjust the group shape in the different surrounding environment of the target, that is, the group shape of the entrapping target can change adaptively according to the distribution of obstacles around the target.

Acknowledgements

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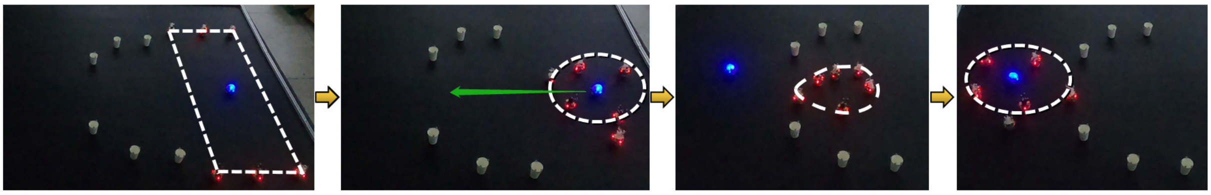

Fig. 10. Scene 1: 6 robots entrap 1 target.

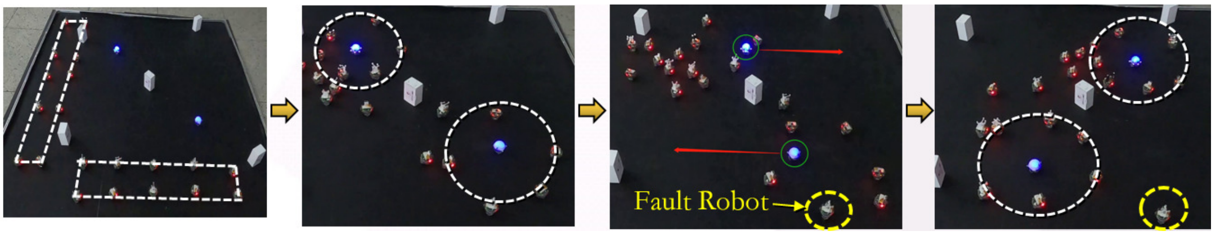

Fig. 11. Scene 2: 20 robots entrap 2 targets.

Table 1. Experiment result.

Experiment	Scene 1(6 robots & 1 target)			Scene 2(20 robots & 2 target)		
	Shape transformation time/s	Entrap success rate	Fault robot	Shape transformation time/s	Entrap success rate	Fault robot
1	97	100%	0	156	100%	2
2	108	100%	0	151	100%	0
3	106	100%	1	145	100%	1
4	91	100%	0	168	100%	1
5	122	100%	0	134	100%	1
Avg.	105	100%	0	151	100%	1

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