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Cooperative Hunting of Multiple Mobile Robots in an Unknown Environment[1)]

CAO Zhi-Qiang　ZHANG Bin　WANG Shuo　TAN Min
(*Institute of Automation, Chinese Academy of Sciences, Beijing* 100080)
(E-mail: zqcao@compsys. ia. ac. cn)

Abstract The hunting task for multiple mobile robots in an unknown environment is modeled as five states, namely, lining-up, random-search, surrounding, catch, and prediction states in the paper. The state transition conditions, and the line-up, search, outflank, catch, predict and direction-optimization strategies are proposed to ensure smooth fulfillment of the task. The target to be captured, called the invader, is endowed a kind of safety motion strategy thus the hunting is more difficult. We illustrate the feasibility of the approach by the simulation.

Key words Multiple mobile robots, hunting, coördination and cooperation

1 Introduction

Coordination and cooperation among multiple robots are of great interest to researchers[1]. Multi-robot safeguard for capturing/enclosing an invader and prevention of invasions by making formation of multiple mobile robots is full of challenge and its achievement so far is significant.

Yamaguchi proposed a novel feedback-control law for coordinating the motion of multiple mobile robots to capture/enclose a target by making troop formation using a formation vectors[2]. Yamaguchi and Arai proposed a control method called "linear autonomous system " for generating the shape of a group consisting of multiple mobile robots to capture a target in [3]. Other related research including the pursuit game, which is also an important topic in distributed artificial intelligence, discusses two kinds of agents: predator and prey in an environment usually modeled in grid. The task is that the multiple predators pursue and finally capture the prey through cooperation, the research focuses being multi-agent cooperation, conflict solving and so on.

This paper focuses on the multiple mobile robots' cooperative hunting in an unknown environment with the moving target of some intelligence.

2 Task modeling

Assume that a proper multi-robot group has been determined according to the hunting task. Also assume that the strategy for the group to make formation and search the environment is feasible in consideration of the limited sensing range of the robots.

Firstly, a robot is selected as the group leader and others as followers. The leader specifies the initial line formation and assigns a unique identification number (ID) to each follower . The leader generates a table that lists the priority for each follower to be the new leader when a new leader is needed. The table is made public within the group. After each robot moves to its respective initial position, the system starts random search . If any one of the robots detects the invader, it informs other robots and the pursuit begins. The strategy to adopt is that after the invader enters the besieging circle formed by multiple ro-

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bots the circle will shrink until the robots catch the invader. Because of the complexity of the task and the environment, the robots may lose track of the invader during chasing. In this case, the system should make decision based on the latest recorded invader position to find the invader again. If the invader cannot be detected within certain steps, the robots should adjust their positions to re-search the environment. The above process is repeated until the robots capture the invader.

In addition, if one robot fails to broadcast the message which is expected by other robots or the broadcast message from the robot is abnormal, then the robot is considered abnormal. If the leader is abnormal, the robot which is normal and has the next hightest priority will temporarily act as the leader. If the abnormal leader does not become normal within certain time, the temporary leader formally becomes the new leader. On the other hand, if one of the followers becomes abnormal, the role of each normal robot remains the same but the priority list, the layout and so on have to be modified. Based on the above description, the hunting task is modeled as five states: lining-up, random-search, surrounding, catch and prediction. The states and the state transitions are shown in Fig. 1.

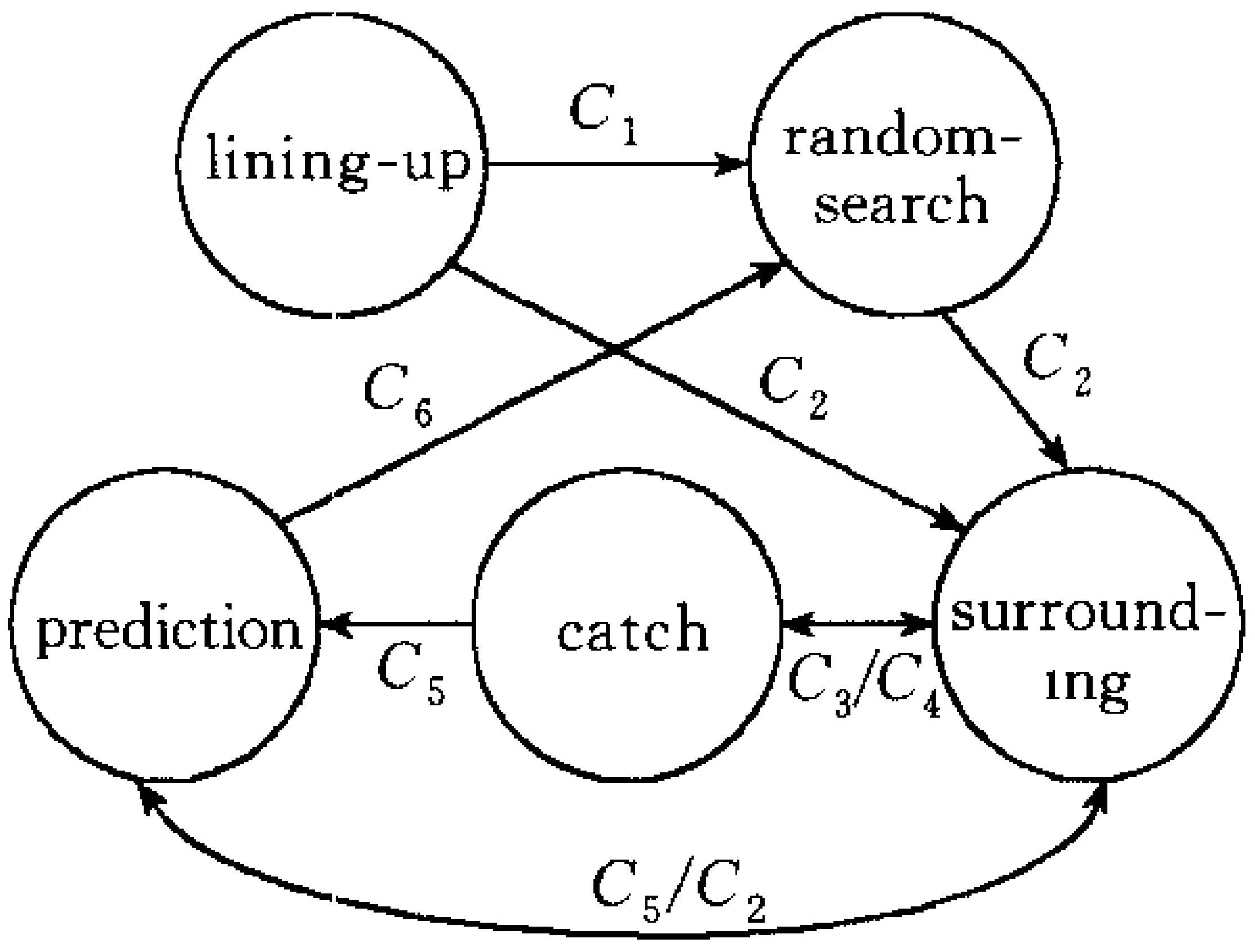

Fig. 1 The states and the state transitions diagram

The state transition conditions $C_t(t=1,2,\cdots,6)$ are described as follows:

C_1 : Multiple robot system has already formed the initial searching formation and none robot has detected the invader

C_2 : At least one robot has detected the invader

C_3 : The condition for the besieging circle to shrink is satisfied

C_4 : The condition for the besieging circle to shrink is not satisfied

C_5 : The robots lose track of the invader

C_6 : The robots still cannot detect the invader after $N_{\text{prediction}}$ steps.

3 The architecture of individual robot

In the paper the robot moves in a 2-D world coordinate system W. In order to fulfil the task an individual robot includes a sensor module, a communication module, a strategy library, a planner and an actuator module as in Fig. 2. During the motion, the planner

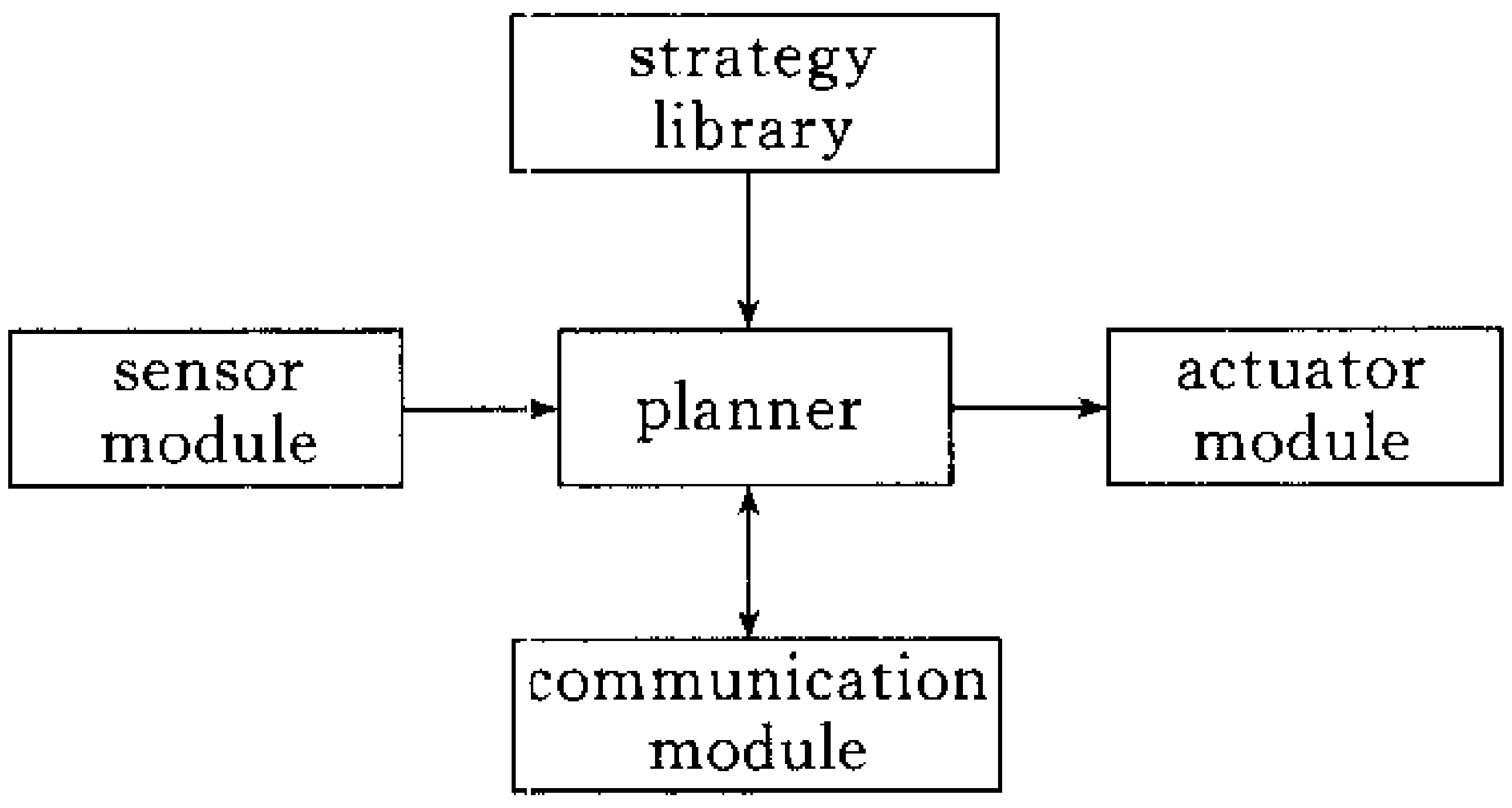

Fig. 2 The architecture of an individual robot

firstly analyses the related communication information and determines the robot's role in the system in accordance with the leader priority and some inner information. Then the planner determines the current task state based on the previous task state, communication information, sensory information and the state transition conditions. After that the planner selects proper strategies from the strategy library to make decision. The obtained moving direction and step size are sent to the actuator module. The necessary strategy library S is defined as follows:

$$S = \{\textit{line-up}, \textit{search}, \textit{outflank}, \textit{catch}, \textit{predict}, \textit{direction-optimization}\}$$

The design of each strategy is as follows.

- Line-up strategy. The strategy is adopted when the robot is in the lining-up state and the robot is required to move towards its initial formation position.

- Search strategy. The robot adopts the strategy when it is in the random-search state. Leader-referenced formation position determination technology is used in this paper[4]. The leader randomly generates its ideal moving direction and decides its actual moving direction as well as step size by adopting the direction-optimization strategy. The decision-making information of the leader is passed to other robots. Upon receiving the motion information from the leader, each follower calculates its ideal formation position and then move towards the position as soon as possible. The ideal moving direction of the leader $(x_r, y_r)^{\mathrm{T}}$ is determined as follows:

$$\begin{bmatrix} x_r \\ y_r \end{bmatrix} = \begin{bmatrix} \cos(-\tau \cdot \mathrm{sing}\rho) & -\sin(-\tau \cdot \mathrm{sing}\rho) \\ \sin(-\tau \cdot \mathrm{sing}\rho) & \cos(-\tau \cdot \mathrm{sing}\rho) \end{bmatrix} \cdot \begin{bmatrix} x_d \\ y_d \end{bmatrix} \tag{1}$$

$$\mathrm{sing}\rho = \begin{cases} -1, & 0.5 > \rho \geqslant 0 \\ 1, & 1 \geqslant \rho \geqslant 0.5 \end{cases} \tag{2}$$

where $(x_d, y_d)^{\mathrm{T}}$ refers to the current moving direction of the robot, τ is an angle randomly rotated, and $\rho(\rho \in [0,1])$ is a random number.

- Outflank strategy. The strategy is used when the robot is in the surrounding state in order to make the invader enter the circular besieging circle shaped by the multi-robot system. The robot can know the positions of other robots and the invader through communication. Based on these positions and the related inner information, the robot makes decision to gain its proper motion position and thus the ideal moving direction is acquired. We denote with P_T the current position of the invader, and we denote with $P_r(ID)(ID=1,2,\cdots,N)$ the positions of all normal robots, where $N(N \geqslant 3)$ is the number of normal robots. $\boldsymbol{P}_T\boldsymbol{P}_r(ID)(ID=1,2,\cdots,N)$ show the direction vectors from the invader to the center of each robot. The ID of the leader is set to L. The decision-making is as follows.

Step 1. establish the polar coordinate system O_1 whose pole is the center position of the invader with the pole axis direction of $\boldsymbol{P}_T\boldsymbol{P}_r(L)$.

Step 2. calculate the coordinates $P_c^m(\lambda_m, \varphi_m)(m=0,1,\cdots,N-1)$ for all robots in O_1, where $\varphi_m \in [0, 2\pi)$.

Step 3. generate the ideal motion positions of all robots. The ideal motion positions are N points that equably distributed in besieging circle centered at the center of the invader with a radius of R_s. These N points are defined as $P_d^n(R_s, \phi_n)(n=0,1,\cdots,N-1)$, where $\phi_n = \frac{2\pi}{N} \cdot n$. Accordingly these coordinates are $P_w(x_n, y_n)(n=0,1,\cdots,N-1)$ in W.

Step 4. determine the ideal motion position. The robot with a larger φ_m selects the ideal position with a larger ϕ_n. If several robots select a same φ_m, the ideal motion positions of these several robots are determined by the leader. This strategy effectively avoids the conflict of selecting the same position.

- Catch strategy. The robot is in the catch state and may catch the invader by reducing the besieging radius. The besieging radius is set to $R_c(R_c < R_s)$ and the robot can obtain the ideal motion position as determined in the outflank strategy. The condition for the besieging circle to shrink is as follows.

Step 1. obtain the $P_r(\min)$, which is $P_r(l)$ that makes the angle between $\boldsymbol{P}_T\boldsymbol{P}_r(L)$ and $\boldsymbol{P}_T\boldsymbol{P}_r(l)(l=1,\cdots,N,l\neq L)$ minimal.

Step 2. establish the polar coordinate system O_2. The pole of O_2 is the center position of the invader and the pole axis direction is $\boldsymbol{P}_T\boldsymbol{P}_r(L)$ when N is an odd number or $\frac{\boldsymbol{P}_T\boldsymbol{P}_r(L)+\boldsymbol{P}_T\boldsymbol{P}_r(\min)}{2}$ when N is an even number.

Step 3. calculate the coordinates $P_b^m(\lambda_m,\gamma_m)(m=0,1,\cdots,N-1)$ for all robots in O_2, where $\gamma_m\in[0,2\pi)$.

Step 4. when $\exists\gamma_i\in\left[\frac{\pi}{2},\pi\right)\cap\exists\gamma_j\in\left[\pi,\frac{3\pi}{2}\right](i,j=0,\cdots,N-1)$ is satisfied, the invader has already entered the besieging circle.

- Predict strategy. When the robot is in the surrounding or catch state, the leader specifies a reference robot based on detecting of the invader and informs other robots of the ID of the reference robot. If the multiple robot system loses track of the invader, the robot should be able to predict the motion of the invader based on the recorded positions of the reference robot and the invader. This is termed as the robot being in the prediction state. If the invader escapes along the reverse direction from the invader to the reference robot and moves in the maximum step size of the robot, the suppositional escaping position of the invader can be calculated. Then the robot acquires its ideal motion position as determined in the outflank strategy.
- Direction-optimization strategy. The robot determines its ideal motion position/direction based on the task state and the strategy mentioned above. In order to get the actual moving direction and step size of the robot based on the current environment, the direction-optimization strategy is proposed, by which the robot obtains the feasible moving direction that has the least angle with the ideal direction on the premise of the predetermined step size.

The robot adopts the range sensors and the detecting zone of each sensor is a sector. The layout of the sensors is shown in Fig. 3 and the arrow direction is the current moving direction of the robot. The robot can know whether there exists obstacles or not in each sector zone as well as the distance to the obstacles. The robot establishes the polar coordinate system O_3 whose pole and pole axis direction are the center position, the current moving direction of the robot respectively. We denote with $P_{rr}(\rho_r,\theta_r)$ the coordinates of the ideal motion position in O_3. The coordinates of the detecting border of the sensor $S_i(i=0,1,\cdots,8)$ in O_3 are $P_s^i(\rho_i,\theta_i)$, where ρ_i is the distance returned by S_i seusing any obstacle except the invader, or else, the maximum sensing range; $\theta_i\in\left[-\pi+\frac{2\pi}{9}i,-\pi+\frac{2\pi}{9}(i+1)\right]$. We denote with $P_a(\rho_a,\theta)$ the coordinates of the next motion position in O_3, where ρ_a is the step

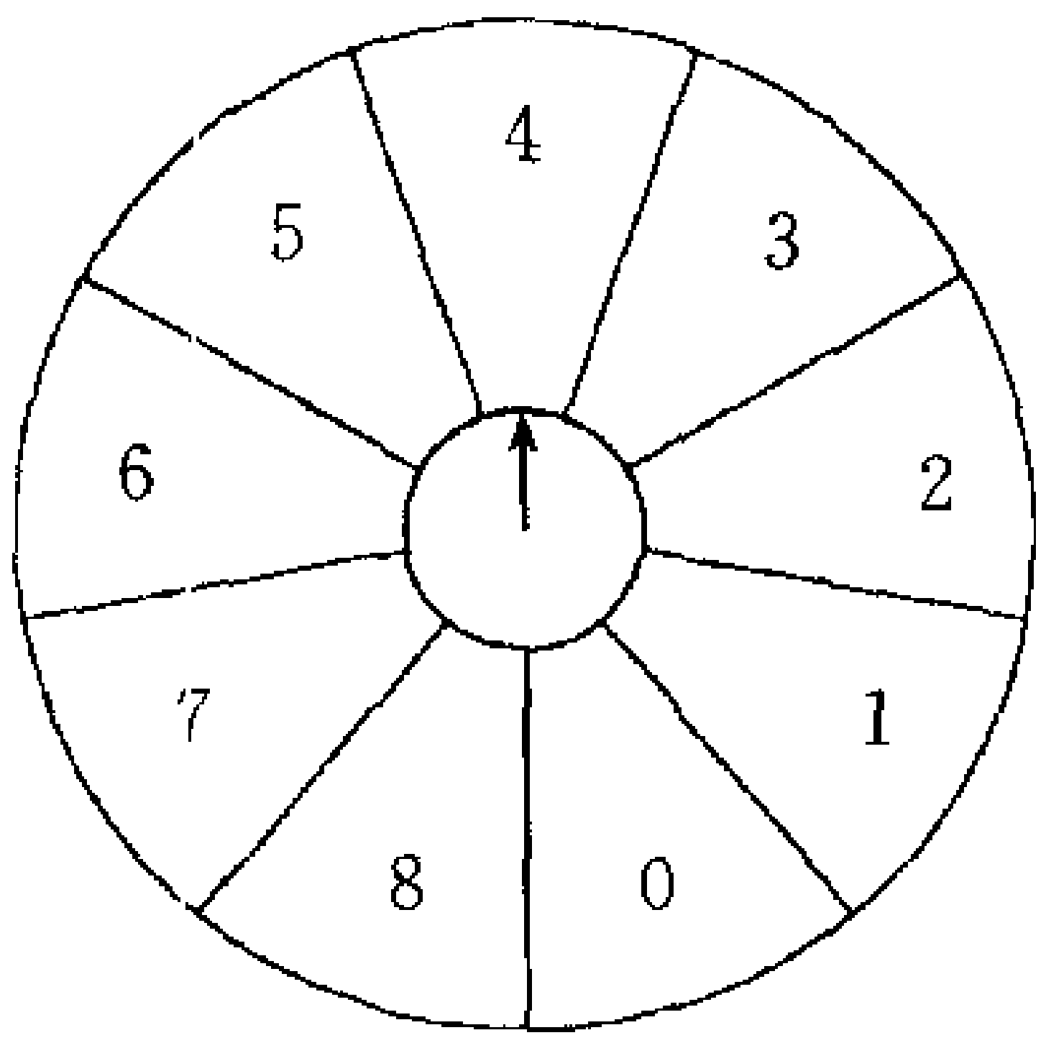

Fig. 3 The layout of the sensors

size determined by the current position, ideal position and the maximum step size of the robot; θ is the angle the robot rotated. The goal is to seek θ within $\left[-\frac{\pi}{2},\frac{\pi}{2}\right]$ of the current moving direction on the premise of the predetermined ρ_a such that the robot moves along the collision-free direction that has the least angle with the ideal direction. On the basis of the sensory information, the distances $P_aP_s^i(i=0,1,\cdots,8)$ from P_a to the detecting border of each sensor should be greater than or equal to the safety distance D_{safe}, namely,

$$P_aP_s^i \geqslant D_{\text{safe}}(i=0,1,\cdots,8) \tag{3}$$

The final value of θ should satisfy the above equation and make $|\theta-\theta_r|$ a minimum. Considering the ith sensor, we have

$$\sqrt{(\rho_a\cos\theta(i)-\rho_i\cos\theta_i)^2+(\rho_a\sin\theta(i)-\rho_i\sin\theta_i)^2} \geqslant D_{\text{safe}} \tag{4}$$

where $\theta(i)$ are the values of θ satisfying the condition of the ith sensor in (3). From (4), we get

$$\cos(\theta(i)-\theta_i) \leqslant \frac{\rho_a^2+\rho_i^2-D_{\text{safe}}^2}{2\rho_a\rho_i} = V \tag{5}$$

When $|\rho_a-\rho_i| \geqslant D_{\text{safe}}$ is satisfied, $\theta(i) \in \left[-\frac{\pi}{2},\frac{\pi}{2}\right]$.

When $\rho_a+\rho_i < D_{\text{safe}}$ is satisfied, $\theta(i) \in \Phi$.

When $\rho_a+\rho_i \geqslant D_{\text{safe}} \cap |\rho_a-\rho_i| < D_{\text{safe}}$ is satisfied, we have

$$\theta(i)-\theta_i \in [-2\pi+\arccos V, -\arccos V] \cup [\arccos V, 2\pi-\arccos V] \tag{6}$$

Any value within the range of θ_i should be suitable for the above equation, therefore,

$$\theta(i) \in \left\{\left[\arccos V-\frac{25}{9}\pi+\frac{2\pi}{9}i, -\arccos V-\pi+\frac{2\pi}{9}i\right]\right\} \cup \left[\arccos V-\frac{7}{9}\pi+\frac{2\pi}{9}i, -\arccos V+\pi+\frac{2\pi}{9}i\right] \cap \left[-\frac{\pi}{2},\frac{\pi}{2}\right] \tag{7}$$

when $\arccos V \leqslant \frac{8\pi}{9}$ is satisfied, and $\theta(i) \in \Phi$, when $\arccos V > \frac{8\pi}{9}$ is satisfied.

The set of the values of θ satisfying the conditions of all sensors is defined as Ω, which is the set of the common values of $\theta(i)(i=0,1,\cdots,8)$. When Ω is not empty, the value of θ can be obtained to make $|\theta-\theta_r|$ minimum and is expressed by $\theta_{\min}$. When Ω is empty, the proper θ can not be found. In this case, the robot turns right angle $\pi/2$ and the step size is zero. Thus the next moving direction of the robot is

$$V_{\text{direction}} = \begin{bmatrix}\cos\beta & -\sin\beta \\ \sin\beta & \cos\beta\end{bmatrix} \cdot \begin{bmatrix}x_d \\ y_d\end{bmatrix} \tag{8}$$

$$\beta = \begin{cases}\theta_{\min}, & \Omega \neq \Phi \\ -\frac{\pi}{2}, & \Omega = \Phi\end{cases} \tag{9}$$

4 The strategies design of the invader

Assume that the invader adopts the same sensor module as that of the robot. When the invader does not sense any static obstacle or other robots, it moves randomly; otherwise, it moves along the safety direction. A kind of safety motion strategy is proposed in this paper. The invader establishes the polar coordinate system O_4 whose pole is its center and the pole axis is the current moving direction. We denote with $P_e^i(\rho_i,\theta_i)$ the coordinates of the detecting border of the sensor $S_e^i(i=0,1,\cdots,8)$ in O_4, where ρ_i is the distance returned by the sensor S_e^i when it senses any obstacle, or else, the sensor is ignored and for convenience ρ_i is far greater than the maximum sensing range of the invader; $\theta_i \in \left[-\pi+\frac{2\pi}{9}i, -\pi+\frac{2\pi}{9}(i+1)\right]$. The K directions are generated based on the current direction and the set Ψ that is expressed as follows:

$$\Psi = \left\{ \psi_k \middle| \psi_k = -\pi + \frac{2k\pi}{K}(k = 0,1,\cdots,K-1) \right\} \tag{10}$$

The safety motion strategy is to select the safety direction from the K directions on the premise of the predetermined step size V_e. The distances from the feasible position $P_n^k(V_e, \psi_k)$ to the detecting border of each sensor should be greater than or equal to the safety distance L_{safe}, thus

$$d_i(\psi_k) = \min(P_n^k P_e^i) \geqslant L_{\text{safe}}(i = 0,1,\cdots,8) \tag{11}$$

The final value of ψ_k should satisfy (11) and make $dis(\psi_k)$ a maximum, that is,

$$dis(\psi_k) = \min(d_0(\psi_k),\cdots,d_8(\psi_k)) \tag{12}$$

$$dis(\psi_{\max}) = \max_{\psi_k} dis(\psi_k) \tag{13}$$

The next moving direction of the invader is as follows:

$$V_{e\_dir} = \begin{bmatrix} \cos\psi_{\max} & -\sin\psi_{\max} \\ \sin\psi_{\max} & \cos\psi_{\max} \end{bmatrix} \cdot \begin{bmatrix} x_e \\ y_e \end{bmatrix} \tag{14}$$

where $(x_e, y_e)^T$ refers to the current moving direction of the invader.

When the invader cannot find a proper direction, it has been captured.

5 Simulations

Simulations are done in order to testify the feasibility of the proposed approach. In the following simulations, a team of robots hunts the invader T in an unknown environment. The fundamental simulation conditions are described as follows:

1) All the robots and the invader know their own positions;

2) The environment is unknown to all the robots and the invader;

3) The robot can recognize the invader;

4) The communication is necessary for the robots to exchange information;

5) The robots have the same sensing range and maximum step size as those of the invader.

The robot and the invader are of round bodies with the radius of 0. 2 and the maximum step size is 0. 3. The maximum detecting range of the sensor is 1. 6. D_{safe} and τ in the direction-optimization and search strategies are 0. 425 and $\frac{\pi}{18}$, respectively. R_s and R_c in the outflank and catch strategies are 1. 48 and 0. 6, respectively. $N_{\text{prediction}}$ is set to 5. K and L_{safe} in the safety motion strategy of the invader are 18 and 0. 38, respectively.

In simulation 1, five robots whose IDs are 1,2,···,5, respectively are adopted to perform the hunting task and the robot of ID 3 is selected as the leader. The hunting process is depicted in Fig. 4. The initial positions of all the robots and the invader are shown in Fig. 4(a). Fig. 4(b) describes the initial formation positions of the robots as well as the position of the invader. Then the robots search the environment randomly under the leader's guidance. When the robot of ID 2 detects the invader (see Fig. 4(d)), it informs other robots and the pursuit starts. Fig. 4(e) exhibits the occasion that the besieging circle shrinks and finally the invader is captured, as shown in Fig. 4(f).

In simulation 2, five robots are initially adopted and the robotof ID 3 is the leader. During the process, when the robot whose ID is 1 can not go on performing the task because of the fault, etc. , other robots continue to move until the invader is captured. Fig. 5 shows the process. The robots start to move from the initial positions as in Fig. 5(a). When the initial line formation is formed, the positions of each robot and the invader are depicted in Fig. 5(b). When the robot of ID 1 moves to the position shown in Fig. 5(c), it stops moving. Other robots go on executing the task. When the robot of ID 4 detects the invader, the besieging circle shrinks and the robotic system captures the invader are

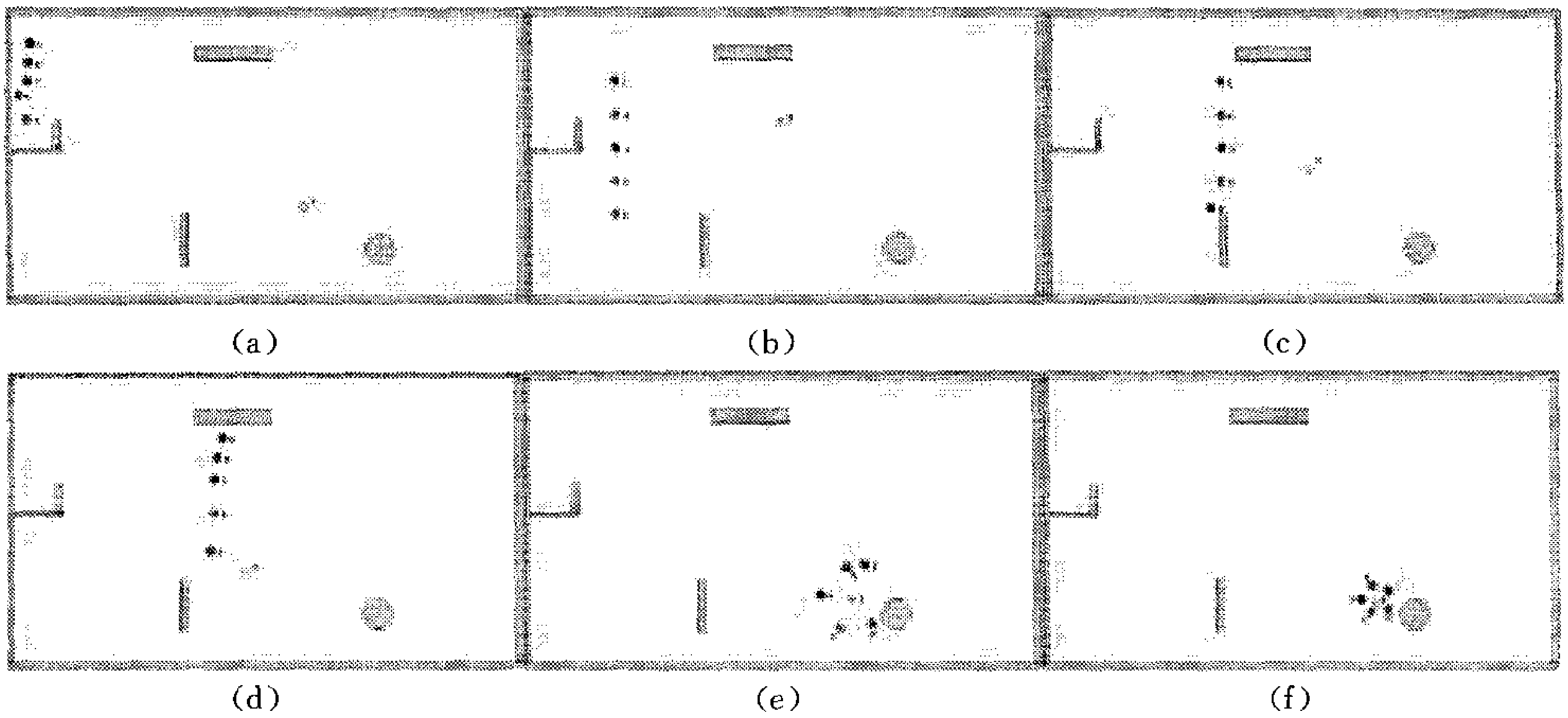

Fig. 4 Selected images for the cooperative hunting process of simulation 1

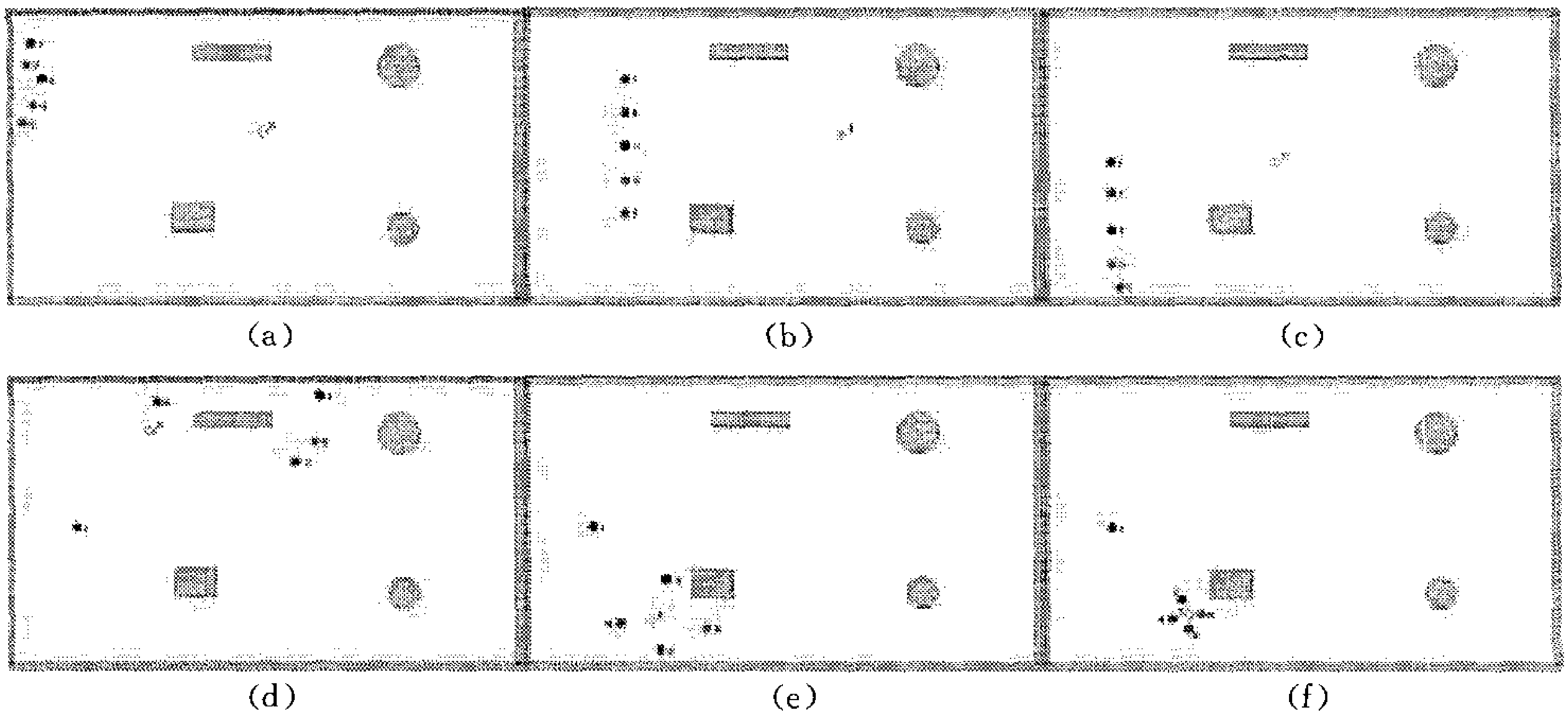

Fig. 5 The result of simulation 2

exhibited in Figs. 5(d～f), respectively. This simulation shows the proposed approach has capability of fault tolerance to some extent.

6 Conclusion

This paper mainly focuses on the problem of cooperative hunting of multiple mobile robots with unknown environment. The task is modeling as five states, and the state transition conditions and a series of strategies are designed to ensure smooth fulfilment of the task. As the invader tries to escape by adopting its safety motion strategy and the difficulty of hunting is increased. Simulation results show the feasibility of the proposed approach.

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CAO Zhi-Qiang Received his master degree from Shan Dong University of Technology in 1999 and Ph. D. degree from Institute of Automation, Chinese Academy of Sciences in 2002, respectively. His research interests include multi-robot system and intelligent robot etc.

ZHANG Bin Received his bachelor degree in Mechatronics from Xi'an Jiaotong University in 1998, and master degree in Automatic Control from Institute of Automation, Chinese Academy of Sciences in 2001, respectively. His research interests include multi-robot systems and embedded sensor networks.

WANG Shuo Received his master degree from Northeastern University in 1998 and Ph. D. degree from Institute of Automation, Chinese Academy of Sciences in 2001, respectively. His research interests include multi robot systems, intelligent control, and system simulation etc.

TAN Min Received his bachelor degree from Tsinghua University in 1986 and Ph. D. degree from Institute of Automation, Chinese Academy of Sciences in 1990, respectively. He is a professor of Institute of Automation, Chinese Academy of Sciences. His research interests include intelligent robot, multi-robot systems, reconfigurable manufacturing system, and complex systems etc.

未知环境中多移动机器人协作围捕的研究

曹志强　张　斌　王　硕　谭　民
（中国科学院自动化研究所　北京　100080）
（E-mail: zqcao@compsys.ia.ac.cn）

摘　要　为了实现多移动机器人在未知环境中的围捕，本文将任务建模为排队、随机搜索、包围、捕捉和预测五种状态．提出了排队、搜索、包抄、捕捉、预测和方向优化策略，结合状态转换条件保证了任务的顺利实现．同时，赋予被捕捉对象（下用 Invader 表示）一种安全运动策略，增加了围捕的难度．仿真结果表明了所提方法的可行性．

关键词　多移动机器人，围捕，协调协作
中图分类号　TP24