Cooperative Control System of Multiple Mobile Robot Using Particle Swarm Optimization with Obstacle Avoidance for Tracking Target

by Dwi Arman Prasetya

PAPER

Cooperative Control System of Multiple Mobile Robots Using Particle Swarm Optimization with Obstacle Avoidance for Tracking Target

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Abstract   In this paper, we propose a cooperative control system with obstacle avoidance for multiple mobile robots using particle swarm optimization (PSO) in an unknown environment to perform tasks that are difficult for a single robot to accomplish. The problem considered in this paper is the exploration of an unknown environment with the goal of finding and tracking targets using multiple mobile robots. The mobile robots only have basic information about the position of other mobile robots and the relative distances between mobile robots and target. PSO has been demonstrated to be a useful algorithm for tracking target applications for multiple mobile robots in unknown environments. The experimental results demonstrate the validity of the proposed cooperative control system with obstacle avoidance of multiple mobile robots that track targets.

Keywords: multiple mobile robots, obstacle avoidance, tracking target, particle swarm optimization (PSO)

1. Introduction

In recent years, multiple mobile robot systems have been successfully used in many fields owing to their ability to perform difficult tasks in hazardous environments, such as robot rescue and space exploration [1]-[3]. Therefore, researchers have paid more attention to cases of searching for one or more targets in an unknown and possibly dangerous (for humans) environment as a task that can be performed by multiple mobile robots [4, 5].

Many potential applications exist for the deployment of small mobile robots. Teams of small robots may potentially carry out surveillance, monitoring, search, and rescue operations [6]. However, small robots have limited mobility ranges, and reduced sensing and computation capabilities owing to their size and power constraints [7, 8].

In the behavioral control approach, primitive behaviors are defined for the mobile robots. Drive commands are generated by aggregating a collection of weighted primitives [9]. Many algorithms in multiple robot systems, such as artificial potential fields [10], the genetic algorithm [11], neural network systems [12, 13], and flocking algorithms [14], have been proposed for controlling multiple mobile robots. However, those algorithms work best for robots traversing a known environment.

The idea of using multiple mobile robots for tracking targets in an unknown environment can be realized by particle swarm optimization (PSO) proposed by Kennedy and Eberhart in 1995 [15]. The actual implementation of an efficient algorithm such as PSO is required when robots must avoid to randomly positioned obstacles in an unknown environment to reach the target point [16]. However, ordinary methods of obstacle avoidance have not yielded good results for route planning. PSO is a self-adaptive population-based method in which the behavior of the swarm is iteratively generated from the combination of social and cognitive behaviors and is an effective technique for collective robotic search problems [17]. When PSO is used for exploration, it enables robots to travel on trajectories that lead to total swarm convergence on some target.

The PSO algorithm is used such that robots may find targets in unknown environments in an area of interest. However, if the environment system becomes complex, the search time required will become longer. In order to improve the original PSO algorithm with respect to the search performance of the multiple robot system, Lu and Han [18] proposed a probability PSO with an information-sharing mechanism for a cooperative control system. As a result of introducing the ideas of the distribution estimation algorithm and niche, each mobile robot is provided with an opportunity to choose an appropriate position in the search space such that the search performance of the robot group can be improved.

This research treats the cooperative control of multiple mobile robots for tracking a target. The control sys-

tem should produce effective motion to reach one or more different positions of the target [19]. Here we only have basic information about the environment, such as the position of each mobile robot and relative distances between the mobile robots and the target. Hence, real-time planning making use of coordination among the mobile robots concerning information on their surrounding environment is necessary.

We developed a cooperative control system with PSO and an obstacle avoidance algorithm in each mobile robot. The problem deals with a number of mobile robots deployed in an unknown environment tracking and reaching their target by avoiding obstacles encountered along the way. We deploy a set of mobile robots at a corner of the space from where they start moving towards a randomly placed target. In this process, the robots broadcast information desired about their surroundings from the sensor condition continuously to a host PC. A circular drift function is used here to effectively avoid collisions of robots with obstacles.

In order to confirm the validity of the proposed control system, the mobile robots are prepared to implement the cooperative control system for tracking targets in unknown environments using PSO and the obstacle avoidance method.

2. Problem Statement

The focus of this study is the creation of control algorithms for a multiple mobile robot system. In our previous research [12], we used a neural network to organize multiple mobile robots. However, when the target position is unknown, setting the weight of the neural network will become complex. Therefore, in this research, we propose a new algorithm to search for and track the target by using PSO in an unknown environment with obstacles.

A simple illustration of solving the problem of searching for and tracking a target in an unknown environment is presented in Fig. 1. Under the initial conditions, the mobile robots are at random positions and move in random directions in the unknown environment. The mobile robots have a mission to search for and track the position of targets and avoid collision with the obstacles.
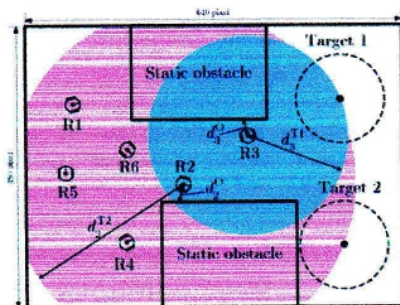

Fig. 1 Concept of the proposed research

The environment and obstacle (i.e., walls and other robots) positions are unknown to each mobile robot. We use video cameras above the environment to acquire the coordinates of the position of each mobile robot and target area. The robots only have information concerning the relative distance to the target area and the positions of other mobile robots. The search radius of each mobile robot is the shortest distance to a target. For example, d_3^{T1} is the closest distance to the target of R3 so the blue space is its search area and d_3^{O} is the distance between R3 and a static obstacle.

3. Cooperative Control Algorithm

3.1 Mobile robot model

The kinematic equations of the two-wheeled mobile robots used in this study are

$$\begin{bmatrix} \dfrac{dx}{dt} \\ \dfrac{dy}{dt} \\ \theta \end{bmatrix} = \begin{bmatrix} \dfrac{\cos(\theta)}{2} & \dfrac{\cos(\theta)}{2} \\ \dfrac{\sin(\theta)}{2} & \dfrac{\sin(\theta)}{2} \\ \dfrac{1}{2l} & \dfrac{1}{2l} \end{bmatrix} \begin{bmatrix} V_L \\ V_R \end{bmatrix} \tag{1}$$

where $\frac{dx}{dt}$ and $\frac{dy}{dt}$ are the velocities of the center of the mobile robot, θ is the angle that represents the orientation of the vehicle, v_i^L and v_i^R are the velocities of the left and right wheels, respectively, and $2L$ is the mobile robot base length. Each mobile robot remembers the position that allows it to achieve its highest performance as a member of some neighborhood of the mobile robots group. It also remembers which mobile robot achieved the best overall position in that neighborhood.

Figure 2 shows the two-wheeled mobile robot model, where $P_i(x_i, y_i)$ is the coordinates of the ith mobile robot position and $\vec{V}_i$ is the velocity of the mobile robot.
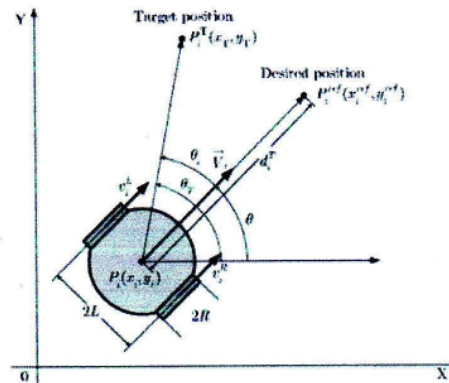

Fig. 2 Model of two-wheeled mobile robot

The evaluation function of the distance between each mobile robot and the target is the distance d between the

current position P_i (x_i, y_i) and the desired position P_i^{ref} (x_i^{ref}, y_i^{ref}) of the robot at the next sampling, and is defined by Eq. (2).

$$d = \sqrt{(x_i^{ref} - x_i)^2 + (y_i^{ref} - y_i)^2} \qquad (2)$$

The error angle to the target θ_e is defined as

$$\theta_e = \theta_T - \theta \qquad (3)$$

where

$$\theta_T = \tan^{-1}\left(\frac{y_T - y_i}{x_T - x_i}\right) \qquad (4)$$

$$\theta = \tan^{-1}\left(\frac{y_i^{ref} - y_i}{x_i^{ref} - x_i}\right) \qquad (5)$$

and in the next sampling program the error angle will be minimized. From Eq. (2), we can determine the position of the nearest target from the robot position, and the mobile robot will decide and choose the final target. The nearest position of the mobile robot to the target will become gBest. Equation (1) is used for determining the direction of the mobile robot toward the target.

3.2 Moving action of mobile robot

The moving action algorithm of each mobile robot in the case of two targets ($T1$ and $T2$) is shown in Fig. 3. At initialization $t = 0s$, each mobile robot has some information such as its own position in the unfamiliar surroundings, the position of the other mobile robots in the surrounding area, and the distance to the target position. This information is used for PSO. Each mobile robot checks the distance between its own position and the target 1 position (d_i^{T1}) and target 2 position (d_i^{T2}). The mobile robots decide the target area nearest themselves. Next, tracking of the shortest path to reach the target is performed by the PSO method.

In each iteration, the mobile robot updates the nearest target position using a Euclidean distance equation. The information on the current position of each mobile robot, gBest, pBest, and $\vec{V}_i(t + H)$, the velocity of the mobile robot, is calculated by the PSO algorithm to obtain the new position of each mobile robot. During the moving action to reach the target area, the mobile robot also checks for the presence availability and distance (d_i^O) of obstacles (i.e., walls and other robots) using a sensor. If there is an obstacle during the moving action toward the target, the mobile robot will use the avoidance algorithm to avoid the obstacle, employing its last position closer to the obstacle as an input to the PSO algorithm to determine its next position.

3.3 Definition of particle swarm optimization

In the PSO algorithm, particles communicate with each other while learning from their own experience, and gradually move to better regions of the problem space. The
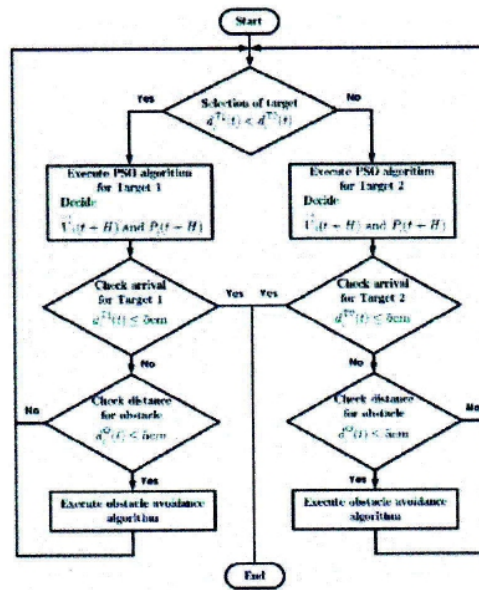

Fig. 3 Flowchart of moving action in the case of two targets

problem space is initialized with random solutions among which the particles search for the optimum one. Each particle randomly searches the problem space by updating itself with the best solution found and the social information gathered from other particles. Within the defined problem space, the system has a certain population of particles. Each particle moves with a random velocity in the search space. The velocities and positions of the particles are constantly updated until all particles have reached the target. Each mobile robot is a particle that communicates with other robots while learning from its own experience in the population, begining with a randomized position $\vec{P}_i(t)$ and randomized velocity $\vec{V}_i(t)$ in the real environment search space.

The problem in an unknown environment is initialized with random solutions among which the robots search for the optimum solution. Each mobile robot randomly searches the problem space by updating itself with the best solution found and the social information gathered from other robots. As in general PSO, the mobile robots navigate through the environment with random velocities while storing their personal previous best position (pBest) and the best position of the entire swarm relative to the target, known as the global best position (gBest). As one mobile robot finds an optimal solution, other robots migrate towards it, in effect exploiting and exploring the best sections of the search space. The velocities and positions of the robots are constantly updated until all robots reach the target position.

Velocity update equations based on PSO are given by

$$\vec{V}_i(t+H) = \omega \vec{V}_i(t) + c_1 rand(*)(pBest_i - \vec{P}_i(t))$$
$$+ c_2 rand(*)(gBest - \vec{P}_i(t)) \quad (6)$$
$$\vec{P}_i(t+H) = \vec{P}_i(t) + \vec{V}_i(t+H) \quad (7)$$

Here, H is the sampling time in the simulation of 40 ms. c_1 and c_2 are the balance factors between the effect of self-knowledge and social knowledge as the particle moves towards the target. $rand(*)$ is a random number between 0 and 1 and is different in each sampling. ω is the inertia weight. $pBest_i$ is the best position of a particle (mobile robot). $gBest$ is the best position within the swarm. $\vec{P}_i(t+H)$ is the new position of the mobile robot in the next sampling. $\vec{P}_i(t)$ is the current position of the mobile robot. $\vec{V}_i(t+H)$ is the velocity of the mobile robots in the next sampling.

3.4 Obstacle avoidance algorithm

The mobile robots are the particles that move through the workspace, gaining a new position at each sampling. A conditional statement checks whether the sensor condition of each mobile robot is active or not. If one of the sensors is active, the obstacle avoidance section of the algorithm is initiated. The detection range of the sensor is fixed at 50 mm.

The obstacle avoidance algorithm can be summarized by the following steps.

Step 1 : Each mobile robot, from the beginning until reaching the target position, always checks the condition of the sensor by scanning from left to right.

Step 2 : If the sensor is active, the mobile robot will execute the interrupt program for obstacle avoidance. Under the interrupt condition, the mobile robot performs a moving action in accordance with the condition of the sensor, as listed in Table 1.

Table 1 Obstacle avoidance moving action of mobile robot

Moving Action	Left Sensor	Front Sensor	Right Sensor
Right pivot	True	False	False
Slow backward	False	True	False
Left pivot	False	False	True
Right pivot	True	True	False
Slow forward	True	False	True
Left pivot	False	True	True
Slow backward	True	True	True

Each mobile robot, after the completion of the obstacle avoidance moving action, sends the sensor condition data to the host PC. Then the sensor data is used to determine the next position using the PSO algorithm. The sensor data is used to confirm that there are obstacles around the mobile robots. If the next position is near an obstacle area, the PSO algorithm will find another position to avoid the obstacle.

4. Developed Multiple Mobile Robot System

In this study, we discuss the cooperative control system of multiple mobile robots using PSO on a 2D plane. To carry out a cooperative target-tracking experiment using real robots, we developed multiple mobile robots and an environment system.

4.1 Developed environment system

In this system, we used the positions of six mobile robots and the relative distances between each mobile robot and the targets, as calculated from image information observed with a video camera above the workspace in a real-time process, as shown in Fig. 4.
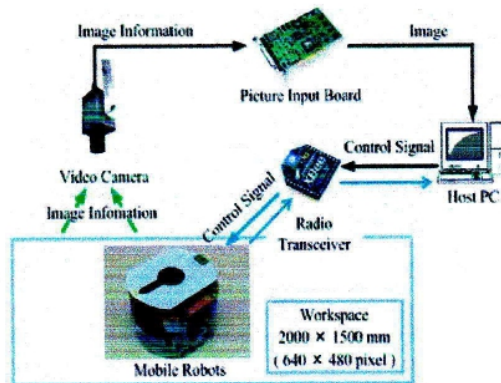

Fig. 4 Environment system

The host PC has two inputs. One is an image from a video camera mounted at the top of the workspace. From the images received by the PC, we obtain information about the position of each mobile robot and the distance from each robot to the target. The other input is real-time distance sensor data received through XBee wireless communication. In this case, the mobile robot alternately receives command signals and sends distance sensor data via XBee wireless communication. The host PC calculates the control signal for each mobile robot using the cooperative control system with the PSO algorithm and sends the result to each mobile robot via XBee wireless communication. In this case, the host PC alternately receives distance sensor data and sends command signals via XBee wireless communication. The sampling time of the control system is set to 40 ms.

4.2 Developed mobile robot

Figure 5 shows the appearance of the developed mobile robot with two wheels, named P-2. The overall height is 55 mm, the diameter is 70 mm, and the total weight of P-2 is 550 g.
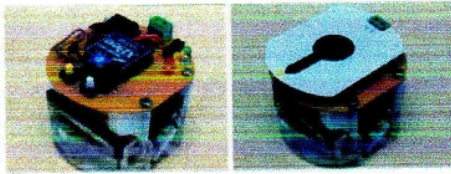
Fig. 5   Developed two-wheel mobile robot: P-2

In each mobile robot, there are three fixed range distance sensors. The sensors are located at the front, right side, and left side of each mobile robot. Each distance sensor has a fixed detection distance of 50 mm with a digital output. The physical specifications of a mobile robot are listed in Table 2.

The mobile robots with AVR ATmega88P as a controller can receive data commands from the host PC and then process the data to generate a moving action and can check the distance sensor condition continuously to detect the obstacle and then send the data to the host PC.

Table 2   Specifications of P-2

| Robot Size	
Height [mm]	55
Diameter [mm]	70
Weight [g]	550
Microcontroller	
Type	AVR ATmega88P
Frequency [MHz]	20
DC Geared Motor	
Type	GWS PICO/STD/F
Max Speed[cm/s]	9.4
Radio Tranceiver	
Type	XBee (3.3V UART)
Frequency Band [GHz]	2.4
Baud Rate Max. [bps]	115200
Distance Sensor	
Type	Sharp GP2Y0D805Z0F
Package size [mm]	13.6x7x7.95
Power Consumption [mA]	5
Range [mm]	50 (Fixed)

5. Experiment

In order to verify the validity of the cooperative control system using PSO to the track target, under several settings, and experiments using the developed mobile robots P-2, were conducted. Six mobile robots are used in this experiment.

5.1 Environment setting

In the experiment, the size of the working space is 200x150 cm. Figure 6(a) shows the appearance of the envi-

ronment without obstacles, and Fig. 6(b) shows the appearance of the environment with obstacles. Each mobile robot is programmed to find the moving action, without crashing into the obstacles or other robots, by the PSO method.

Here, it is assumed that each mobile robot has information about the distance between its current position and the target area, its position, and positions of other robots close to it.
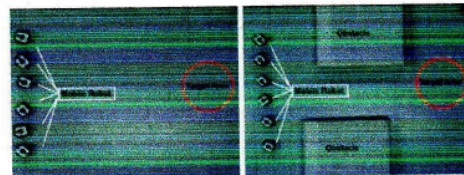
(a) Environment without obstacles   (b) Environment with obstacles

Fig. 6   Environment setting with one target

During the experiment, the mobile robots we fabricated make full use of the real-time information attained by updating the coordinates of each mobile robot using images from a video camera positioned above the workspace and the distance sensor condition, in this case, the Euclidean distances of the individual robots relative to the target, to analyze the status of their relative current positions. The basic PSO algorithm has the obstacle avoidance algorithm to handle obstacle (i.e., walls or other robots) avoidance using cooperative and collective robotic search applications to reach the target.

5.2 Experimental results

The parameters of PSO in the experiment are set as follows: $c_1=c_2=1.5$, $\omega = 0.5$, $rand(*) = [0, 1]$, and the maximum velocity of a mobile robot is 9.4 cm/s.

By the PSO method, the mobile robots can find and move towards the target area in an unknown environment. The results are shown in Figs. 7(a)-7(d) to Figs. 10(a)-10(d). At the initial time $t = 0$ s, each mobile robot is at a random position in the unknown environment.

In the first experiment, we set an environment with one target area and without any obstacles. At the initial time $t = 0$ s, each mobile robot position is as shown in Fig. 7(a). At $t = 45$ s, several mobile robots that have reached the target area by using cooperative control algorithm with the PSO method are shown in Fig. 7(b). From $t = 45$ s to $t = 100$ s, the other mobile robots are still trying to find the target area using $gBest$ data from the other mobile robots that had already found the target. At the end of the experiment, $t = 145$ s, all of the mobile robots have reached the target area as shown in Fig. 7(d).

In the second experiment, we include two obstacles in the unknown environment with one target area. Figure 8(a) shows the initial position of each mobile robot in the environment. Up to $t = 90$ s, the mobile robots are still trying to find the target area, as shown in Fig. 8(b). The $gBest$ value

(a) $t = 0$ s - $t = 45$ s   (b) $t = 45$ s - $t = 90$ s

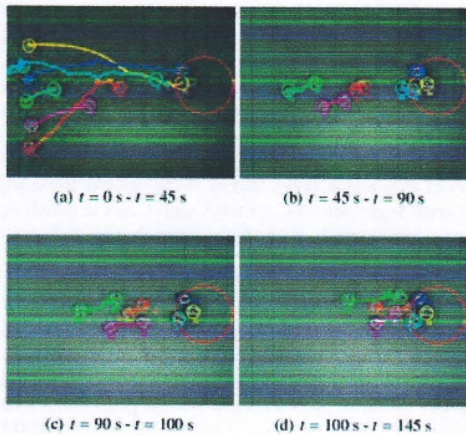(c) $t = 90$ s - $t = 100$ s   (d) $t = 100$ s - $t = 145$ s

Fig. 7 Tracking actions of mobile robots in unknown environment without obstacle and with one target area

is obtained from the mobile robot with the green line. At $t = 110$ s, Fig. 8(c) shows that several mobile robots has reached the target area. Each mobile robot can reach the target area while cooperatively avoiding the obstacles and other mobile robots by $t = 160$ s, as shown in Fig. 8(d).

(a) $t = 0$ s - $t = 45$ s   (b) $t = 45$ s - $t = 90$ s

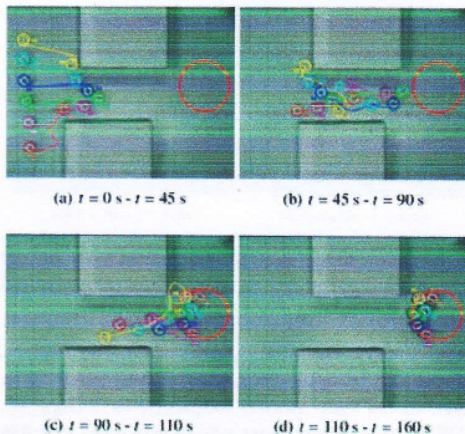(c) $t = 90$ s - $t = 110$ s   (d) $t = 110$ s - $t = 160$ s

Fig. 8 Tracking actions of mobile robots in unknown environment with two obstacle and one target area

Figures 9(a)-9(d) show snapshots of the movements of six mobile robots in an unknown environment with two target areas and no obstacles. Each mobile robot can move towards the target area quickly while cooperatively avoiding other mobile robots.

At $t = 45$ s, the mobile robots divided into two groups. The first group chose the target area in the top right and the second group chose the target area in the bottom right of the screen, as shown in Figs. 9(b) and 9(c). All of the

mobile robots had reached the target area by $t = 155$ s, as shown in Fig. 9(d).

(a) $t = 0$ s - $t = 45$ s   (b) $t = 45$ s - $t = 90$ s

(c) $t = 90$ s - $t = 120$ s   (d) $t = 120$ s - $t = 155$ s

Fig. 9 Tracking actions of mobile robots in unknown environment without obstacle and with two target areas

In the next experiment, we set the environment to have two target areas and two obstacles. At the initial time, $t = 0$ s, each mobile robot is at a random position in the unknown environment. By $t = 90$ s, one of the mobile robots has reached one of the target areas and another mobile robot is near one of the target areas, as shown in Fig. 10(b). After $t = 120$ s, four mobile robots have reached the target areas, as shown in Fig. 10(c). Each mobile robot has moved towards a target area while cooperatively avoiding obstacles and other mobile robots by $t = 170$ s, as shown in Fig. 10(d).

(a) $t = 0$ s - $t = 45$ s   (b) $t = 45$ s - $t = 90$ s

(c) $t = 90$ s - $t = 120$ s   (d) $t = 120$ s - $t = 170$ s
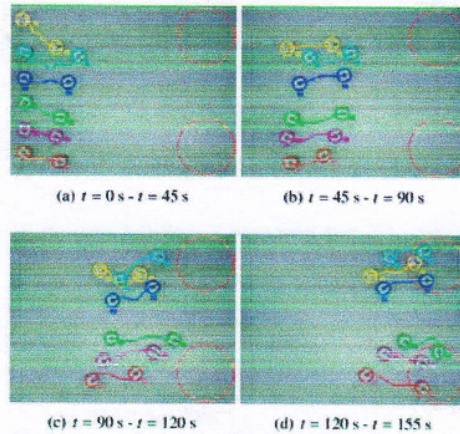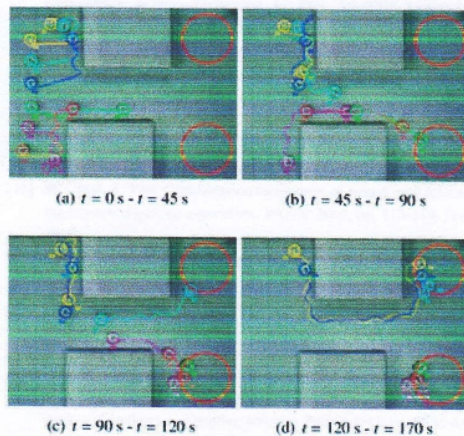
Fig. 10 Tracking actions of mobile robots in unknown environment with obstacles and with two target areas

In the last experiment, we set a moving target in the environment. The targets can move with constant velocity and follow the white dashed lines, as shown in Fig. 11(a). At the initial time $t = 0$ s, each mobile robot is at a random position in the home base area, and the $gBest$ value can be obtained from the mobile robot with the light blue line. The target starts moving when the distance between the target and one of the mobile robots is less than 15 cm as shown in Fig. 11(a). After $t = 30$ s, the target starts to move following the white dashed line. Five mobile robots can track the moving target while continuously updating the distance between themselves and the target. The $gBest$ value at this time is obtained from the mobile robot with the red line, as shown in Fig. 11(b). Figure 11(c) shows snapshots of the five mobile robots still tracking and following the moving target until it stops in the home base area followed by the five mobile robots, as shown in Fig. 11(d).

(a) $t = 0$ s - $t = 30$ s   (b) $t = 30$ s - $t = 70$ s

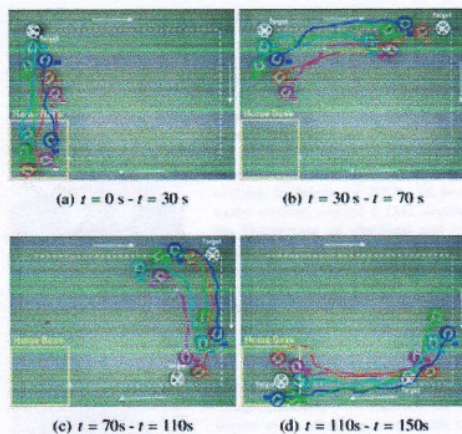(c) $t = 70$ s - $t = 110$ s   (d) $t = 110$ s - $t = 150$ s

Fig. 11   Tracking actions of mobile robots in unknown environment with moving target

The moving actions of each mobile robot in an unknown environment to a target area are shown in Figs. 7-11. Each mobile robot moves from the current position to one of the targets at its preassigned velocity. Each mobile robot moves to the nearest selected target as a result of the PSO method and the cooperative control algorithm.

The results are presented in the conclusions to demonstrate the validity of the proposed cooperative control system in which PSO is used to tracking the target.

6. Conclusions

In this paper, we proposed a cooperative control system for multiple mobile robots in which PSO is used to track the target. The PSO control system enables effective motion for each mobile robot to reach one or more different positions of the target. The position of the globally best particle in each iteration is selected and reached by each robot sequentially. Moreover, the positions of obstacles are detected by the robot sensor and applied to update the information on the environment. The experimental results demonstrate the validity of the proposed cooperative control system with obstacle avoidance for multiple mobile robots tracking a target.

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Malang, Juli 2019
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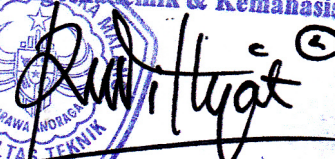
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