Single Target Search and Capture based on Random Sensor Deployment in Mobile Sensor Networks

Jianying Zheng, Haibin Yu, Meng Zheng, Wei Liang, and Peng Zeng

***Abstract*—**this paper addresses the problem of coordinating multiple agents in chasing and capturing a single mobile target, where the objective of a group of agents is to reduce the time of chasing and capturing the target with the aid of wireless sensor networks. Different from the previous algorithms, our research takes two factors into consideration: the non-deterministic target information obtained from the deployed sensor networks and the limited communication range of the mobile agents. The non-deterministic target information is described by a probabilistic method and the limited communication range is handled with keeping the agents within a suitable distance. Combining the above two aspects, we can efficiently guide the agents to chase and capture the mobile target and the time of chasing and capturing can be greatly reduced. The algorithm proposed is particularly applicable to two cases: one is the situation where two or more agents are required to chase and capture; the other is the situation where it is very difficult for sensors to determine which agent they should send the sensing information to. Finally, we have done many simulations and experiments to demonstrate the performance of the algorithm proposed in the paper.

***Index Terms*—**mobile sensor networks, multi-agent systems, coordination control, wireless sensor networks, probabilistic strategies, motion planning, limited communication range.

I. Introduction

Along with the development of wireless sensor networks, the research of mobile sensor networks becomes extremely popular due to their capabilities of both sensing and acting simultaneously. The mobile sensor networks are made of sensors and actors so that they can both sense the environmental information or the target information in the environment and take decisions immediately according to the sensing information [1, 2]. The sensor nodes deployed in advance in the interested regions can enhance the capability of the actors to observe the environment or the targets in the environment, because the actors now can perceive the regions far from their current locations with the aid of the deployed sensor networks rather than the local regions around the actors. Therefore, the actors are able to obtain global observation information and make optimal decisions in place of local observation and suboptimal decisions [3].

The concept of mobile sensor networks can be applied into many real applications. In search and rescue operations, we often need to search an environment for survivors who stay still or move randomly, with the aid of sensor nodes deployed in the environment ahead of time. For example, a fireman can put out a building-fire and rescue people more effectively with the help of sensor nodes deployed. In the nuclear industry, people are not allowed into disaster areas, so all the tasks of clearance are required to be done autonomously. Therefore, an effective solution is to design autonomous agents such as robots to finish the tasks based on the information obtained from sensor nodes deployed before the disaster. Additionally, in military fields, we are always required to locate, chase, and capture single or multiple hostile targets that appear in the strategically important region where sensor nodes are deployed in advance.

The systems with the concept of mobile sensor networks are actually effective for many applications because such systems can improve the performance of finishing the tasks. For example, they can reduce the time of chasing and capturing the targets moving in the regions where sensor nodes are deployed. But numerous challenges also need to be discussed and solved at the same time. These challenges are summarized as three aspects: (1) the non-deterministic sensing information due to the limited capability of sensor nodes; (2) the communication delay and packet loss as a result of transmitting information through networks; and (3)

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the limited communication range of the agents (actors) often found in the physical acting agents. The second challenge is deeply examined in [3]. However, this paper will concentrate on the first and third challenges.

In the paper, the non-deterministic sensing information is described by a probabilistic method. The detected information from sensor nodes are represented by a row vector and the elements of the row vector represent the probability at time t that the target is around the corresponding sensor node. Based on the probabilistic sensing information, the agents (actors) can make better decisions where the target is located currently. Additionally, we try to keep the distance between different agents suitable, in order to avoid obstacles and maintain communication relationship. By combining the two aspects mentioned, the target moving in the pre-defined regions can be found effectively and captured successively in shorter time comparing with the previous algorithms.

The remainder of this paper is organized as follows. Section II describes the related work about multi-agent coordination. Section III provides the problem formulation and definition. Section IV offers the coordination algorithm with multiple agents chasing and capturing a single mobile target with the aid of sensor nodes deployed in the interested regions. Section V presents the simulation and experimental results to demonstrate the performance of the coordination algorithm proposed in this paper. Finally, Section VI draws conclusions and discusses future work.

II. RELATED WORK

The problem of controlling a swarm of autonomous agents in chasing and capturing single or multiple targets is explored in the fields of robotics, pursuit-evasion games, and sensor networks. In [4, 5], C. Clark proposed using the concept of dynamic robot networks to plan paths for multiple robots moving in the same environment. In their work, limited sensing range and limited communication range are assumed. At the beginning, each robot merely knows its own initial and end positions. The essential idea is that the robots can form robot networks in order to share the sensing environmental information from different robots when these robots move close to each other or near to their neighbors. Based on the information, the robots can plan more effective paths, along which static obstacles and collisions with other robots can be avoided. However, these robot networks are formed passively and there is no method to control the dynamical robot network. That implies that when or where to form robot networks is not controllable. In [6], the authors take the limited communication range of robots into consideration in multi-robot area exploration. The robots are required to maintain a mobile network so that they can communicate with each other and have the same view of the environment. The limited communication range of robots is concerned as well in [7, 8]. Other typical work on multi-robot coordination can be seen in [9, 10, 11]. (Note: in the field of robotics, robots are assumed to be equipped with sensors that can only sense the local range. Therefore, only suboptimal decisions can be made according to local information. However, in this paper global information can be obtained with the aid of sensor nodes deployed in advance. So it is possible for agents (actors or pursuers) to make optimal decisions. That is the largest difference from work in this paper.)

A probabilistic framework for pursuit-evasion games is developed in [12]. In the framework, the locations of the evaders are described by a probabilistic method. Then a “greedy” policy is proposed to control a swarm of autonomous agents in the pursuit of one or several evaders. At each instant of time, this policy guides the pursuers to the locations that maximize the probability of finding an evader at that particular time instant. Under wild assumptions, this policy can guarantee that an evader is found in finite time and that the expected time needed to find the evader is finite as well. The relative work based on the probabilistic framework can be seen in [13, 14, 15, 16]. In [16], the probabilistic strategies are used to guide multiple robots to pursue a non-adversarial evader, with the aim of reducing the time of capturing the evader. In the strategies, the environment where all the activities occur is divided into several cells. The current location of the target is described as a row vector, and the elements of the vector represent the probability that the evader is in the corresponding cell. Then several different cost functions are designed to direct the movement of the pursuers. However, here the limited communication range of robots is not considered. An implicit assumption is that the robots can communicate with each other at any time and any place. Another assumption is that the probabilistic locations of the evader can be obtained by robots themselves, regardless of the distance between the evader and the robots. Nevertheless, both assumptions are not available in some actual situations.

The coordination problems can be considered from a new point of view and may have new solutions along with the development of sensor networks [17, 18, 19, 20, 21, 22]. The advantages of sensor networks are that global observation information is possible to provide due to sensor nodes deployed in advance in the interested regions. However, many challenges come with introducing the sensor networks. One challenge is about the inaccurate sensing information provided by the sensor nodes due to the limited capability of sensors. Another challenge involves the communication delay and packet loss caused by the information transmission through the networks. In [3], the authors consider the problem of pursuit-evasion games, where the objective of a group of pursuers is to chase and capture a group of evaders in minimum time with the aid of sensor networks. They address the challenge of inconsistency measurements due to communication delay, packet loss, and false detection, and then develop a real-time hierarchical control system named ***LochNess***, which decouples the estimation of evader states from the control of pursuers via multiple layers of data fusion. Based on the work in [3], we further take the limited communication range of agents into consideration in this paper. Then we attempt to maintain the agents within a mobile network for two reasons as follows: (1) to keep the consistency of the measurements of the target; and (2) to avoid failures of capture when the agent that finds the target is broken down or when two or more agents are required to capture the target (for example, when the target is adversarial so that it is not safe enough for single agent to capture independently).

III. PROBLEM FORMULATION AND DEFINITION

In this paper, we consider the problem of coordinating multiple agents (actors or pursuers) over an interested region to chase and capture single mobile target with the aid of sensor nodes deployed in advance. In order to formulate the problem, we first have to define some variables. The interested region where all the activities occur is a convex environment and is denoted by $\Omega \in \Re^2$. The area of the region is large enough to ignore the edge effect caused by the deployment of sensor nodes. In addition, we assume that there are no static obstacles in the region and the wireless communication capability of agents is merely determined by the distance, regardless of other factors caused by the environment, such as the multi-path interference and the barrier reflection.

The set of agents (actors or pursuers) is denoted by $A = \{A_i, i = 1,2,\ldots,n\}$ where n represents the number of agents used to chase and capture the target. The agents are assumed to be omni-directional and the speed is denoted by $v \in (v_{\min}, v_{\max})$ where $v_{\min}$ and $v_{\max}$ represent the minimum and maximum speed that the agents can reach respectively. The limited communication range of agents is assumed and the maximum communication range is denoted by $d_{\max}$. The location state of the j^{th} agent at time t is denoted by $x_j(t), j = 1,2,\ldots,n$. The initial value of variable $x_j(t)$ is denoted by $x_{j0}, j = 1,2,\ldots,n$.

The set of sensor nodes is denoted by $S = \{S_i, i = 1,2,\ldots,m\}$ where m represents the number of sensor nodes deployed in the interested region in advance. The sensing range and the communication range of a sensor S_i are denoted by r_i and R_i respectively. The location of a sensor S_i is denoted by $s_i = (x_i, y_i) \in \Omega, i = 1,2,\ldots,m$. Once the nodes are deployed, their locations are fixed.

In addition, we assume that the target is non-adversarial and the speed of the target is always lower than that of agents. The location state of the target at time t is denoted by $x^e(t)$. Finally we define a capture event as the occurrence of $\|x_i(t) - x^e(t)\| \le \varepsilon, \exists i$ where ε is a constant determined by the users according to the requirements of the real applications. The definition of the capture event implies that the capture happens successfully if any agent travels close enough to the target.

Therefore, what we need to do is to design a coordination algorithm, which can guide the agents to travel to the current location of the target with minimum time. So the coordination problem is then defined as the determination of the paths for the agents such that the probability of capture is maximized at any given time.

IV. COORDINATION ALGORITHM

Based on the problem formulation and definition in section III, this section is going to present the coordination algorithm, which can guide the agents to chase and capture the target more effectively. The algorithm is composed of four parts. The first part is about the sensor models, which involve the way of deploying the sensor nodes, the sensing mode, and the sensing area of the sensor nodes. The second part involves the sensor networks, which include the sensor coverage, the sensor connectivity, and the expression way of the location of the target. The third part concerns about the agent models, which especially concentrate on the way of handling the limited communication range of agents. The last part is about the coordination algorithm, which offers the updated equation of the location states of the agents and the corresponding geometric interpretation. More details will be provided in the following discussion.

A. Sensor Models

The sensor models are very basic for the coordination algorithm. The region where the sensor nodes are deployed is assumed to be a two-dimension plane $\Omega \in \Re^2$ as presented in section III. The sensor nodes are assumed to be deployed manually instead of randomly in favor of analyzing the topology of the sensor networks in the next part.

Then we describe the sensing models, including both the signal-strength and binary sensor models. A signal-strength model reports the range to a nearby target, while a binary model reports a binary value indicating whether an object is detected near the reporting sensor. Therefore, the signal-strength sensors can provide better accuracy than the binary sensors. In the signal-strength model, each sensor records the sensor's signal strength at time t as in equation 1.

$$z_i(t) = \begin{cases} \dfrac{\beta}{1+\gamma\left\|s_i - x^e(t)\right\|^{\alpha}} + \omega_i^s & if \left\|s_i - x^e(t)\right\| \le r_i \\ \omega_i^s & if \left\|s_i - x^e(t)\right\| > r_i \end{cases}$$
(1)

where α, β, γ are constants related to the sensor type, and ω_i^s is a random variable that satisfies the standard Gaussian distribution. The sensing area of the i^{th} sensor node is assumed to be a disk centered at sensor s_i with radius r_i in the signal-strength sensor model. This sensor model is a general model available for many sensors and has been used frequently [18, 21, 22].

However, in the binary sensor model, the sensing area R_s can have an arbitrary shape but it is always known to the system. The value $z_i(t)$ that the i^{th} sensor can take is only in the set $\{1,0\}$. At time t , the i^{th} sensor reports $z_i(t) = 1$ when it detects a moving object in R_s , and $z_i(t) = 0$ otherwise.

B. Sensor Networks: Coverage and Connectivity

In this paper, the sensor networks are used to collect and transfer the location information of the target. So it is very necessary to consider the coverage problem and the connectivity problem in sensor networks. As shown in Fig.1, we have assumed that the sensor nodes are deployed regularly, the sensing range of the sensor nodes is a constant r for any sensor node, and the distance between any neighboring nodes is denoted by d . Then it is not difficult to demonstrate that the complete coverage of the interested region can be guaranteed if $d \le \sqrt{2}r$. Additionally, we have assumed that the communication range of the i^{th} sensor node is denoted by R_i and that R_i is equal to R for any sensor node where R represents a constant related to the sensor type. As a result of the work by Zhang and Hou in [23], the connectivity can be guaranteed in terms of Theorem 1 as follows.

Theorem 1 *When the number of sensors in any finite area is finite, a necessary and sufficient condition for the complete coverage of a convex region to imply connectivity is* $R \ge 2r$

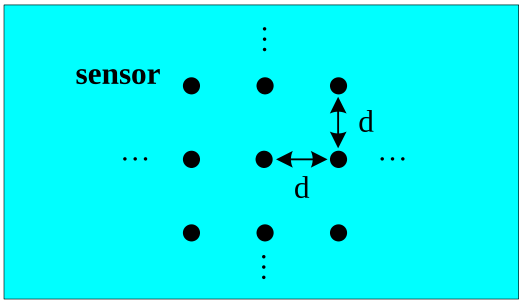

Fig.1. Deployment of the sensor nodes

The coverage and connectivity can guarantee that the target can be detected wherever it is and that the detection information can be transferred to the agents through the sensor networks. The location state of the target at time t is denoted by a row vector $p(t) = [p_1(t), p_2(t), \ldots, p_m(t)]$ where values $p_1(t), p_2(t) \ldots p_m(t)$ represent the probability that the target is in the corresponding sensor node. The elements of the row vector are obtained according to the signal strength received by the sensor nodes as in equation 2.

$$p_i(t) = z_i(t) / \sum_{i=1}^{m} z_i(t), i = 1,2,\ldots,m \qquad (2)$$

C. Agent Models

The agents involved in this paper are used to chase and capture the target. There are many constraints to restrict the agents abstracted from the physical entities. However, this paper concentrates mainly on the limited communication range of the agents, which is very universal in practice. Moreover, it is very necessary to consider the limited communication range of the agents in multi-agent systems because of the importance of the information exchange in coordinating multiple agents to work together.

In addition to the description in section III, we assume that the distance between the i^{th} agent and the j^{th} agent at time t is denoted by $d_{ij}(t) = d(x_i(t), x_j(t)) = \left\|x_i(t) - x_j(t)\right\|$. The minimum distance between two agents is denoted by $d_{\min}$ in order to avoid obstacles among agents. The maximum communication range and the preventive communication range are denoted by $d_{\max}$ and d_{pre} respectively. The value d_{pre} is designed to avoid total loss of communication between a pair of agents.

The basic idea on handling the limited communication range is maintaining the agents in a mobile network so that they can communicate with each other through single-hop or multiple-hop. In this paper, we attempt to keep each agent at least communicating with one other agent. As shown in Fig.2, the agents are always in the same network when the number of agents is less than four. Otherwise, the number of the networks formed by the agents is able to be one or more. For example, when the number of the agents is four, they can form either one network where all the agents are in the same network or two networks where the agents are divided into two sub-networks. The method of maintaining mobile networks has two advantages: (1) improving the robustness of the system when any agent is possible to break down during the operation; and (2) improving the capability of the system to carry out very complex tasks requiring two or more agents.

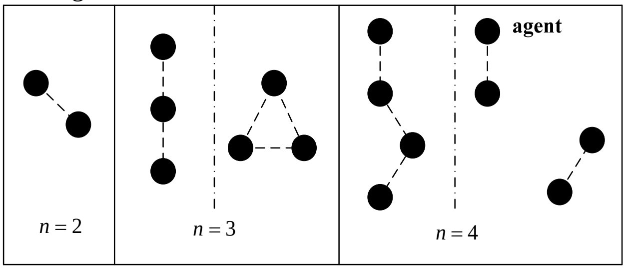

Fig.2. Possible networks formed when the number of agents is not more than four.

D. Coordination Algorithm

The coordination algorithm is used to guide the agents to move towards the current location of the target with minimum time. So the key step is to offer the updated equation of the states of the agents. In general, the location states of the agents are determined by the current location states and the speeds of the agents. However, in this paper we have assumed that the speeds of the agents are constant while the directions are able to change. The directions of the agents are determined by the current location states of both the target and other agents.

The current location state of the target is determined by the row vector $p(t)=[p_1(t), p_2(t),\ldots, p_m(t)]$. In order to reduce the time of capturing the target, we have to maximize the probability of capture at any given time. Therefore, the location of the sensor node with the greatest corresponding probability is selected as the current location of the target at time t as in equation 3.

$$K=\arg\max_k\{p_k(t), k=1,2,\ldots,m\} \quad (3)$$

where K represents that the location of the K^{th} sensor node is approximated as the location of the target.

The other agents are able to make an affect on the directions of the agent under certain conditions. Nevertheless, only the agent with the minimum distance to the current agent is considered. This agent is determined as in equation 4.

$$J=\arg_j\{\min\{d_{ij}(t), j=1,2,\ldots,n, j\neq i\}\} \quad (4)$$

where J represents that the location of the J^{th} agent will influence the directions of the current agent.

In addition, we assume that the internal time is denoted by ΔT , which is decided by the user. Then the coordination algorithm can be described as follows.

(1) If $d_{iJ}\leq d_{\min}$,

Then $x_i(t+\Delta T)=x_i(t)+\dfrac{-(x_J(t)-x_i(t))}{\|x_J(t)-x_i(t)\|}\Delta T$

(2) If $d_{\min}<d_{iJ}\leq d_{pre}$

Then $x_i(t+\Delta T)=x_i(t)+\dfrac{s_K(t)-x_i(t))}{\|s_K(t)-x_i(t)\|}\Delta T$

(3) If $d_{pre}<d_{iJ}\leq d_{\max}$

Then

$$x_i(t+\Delta T)=x_i(t)+\frac{(x_J(t)-x_i(t))+(s_K(t)-x_i(t))}{\|(x_J(t)-x_i(t))+(s_K(t)-x_i(t))\|}\Delta T$$

(4) If $d_{iJ}>d_{\max}$

Then $x_i(t+\Delta T)=x_i(t)+\dfrac{x_J(t)-x_i(t))}{\|x_J(t)-x_i(t)\|}\Delta T$

where d_{iJ} represents the distance between the i^{th} agent and the J^{th} agent, and the definitions of $d_{\min}$, d_{pre}, $d_{\max}$ are the same as that in section III.

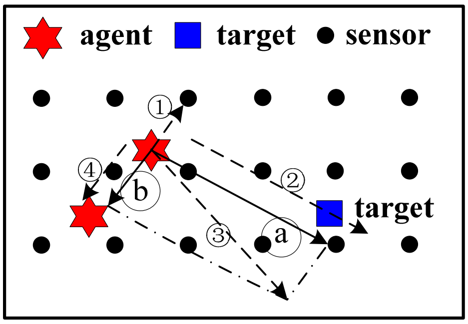

Fig.3. Geometric interpretation of the coordination algorithm

In order to understand the coordination algorithm better, we have provided a geometric interpretation as shown in Fig.3. The directions ⓐ and ⓑ in Fig.3 are determined by the location of the target and the closest neighboring agent respectively. The directions ①, ②, ③ and ④ represent the possible directions in which the agents are able to move. When the agent is close to its nearest neighboring agent, the direction ① will be selected in order to avoid obstacles among agents; when the agent is in the appropriate scope with other agents, the direction ② will be selected in order to move to the target as soon as possible; when the agent is a bit far from other agents, the direction ③ will be selected to avoid the total loss of communication; when the agent is extremely far away from its neighbors, the direction ④ will be selected to recover the communication.

V. SIMULATIONS AND EXPERIMENTS

In order to demonstrate the performance of the coordination algorithm proposed in this paper, we have done many simulations and experiments in this section. The simulations and experiments were done in a rectangle region with the horizontal length $L_1 = 200$ and vertical length $L_2 = 100$. There are two hundred sensors deployed in the region. The horizontal and vertical distances between two sensors are $L_{10} = 10$ and $L_{20} = 10$ respectively. The sensing range r is not less than $5\sqrt{2}$ so that the full coverage of the region can be guaranteed. In addition, the communication range R is not less than $2r$ so that the connectivity can be guaranteed in the deployed sensor networks. So the target can be detected and the information can be transmitted to agents wherever the target is.

The single target moves randomly in the region with the velocity $v = 2$. The agents attempt to chase and capture the target with the velocity $V = 3$. The other parameters are set as follows: $d_{\min} = 10, d_{pre} = 25, d_{\max} = 30$. The simulation results are shown in Fig.4, Fig.5 and Fig.6 respectively. Fig.4 provides the trajectories of two agents and one target along which they move; fig.5 supplies the distances between two agents with respect to the time; and fig.6 gives the distances from the agents to the target with respect to the time. In the simulation shown in Fig.4, the agents can move towards the location of the target due to the information of the target obtained from the sensor networks deployed in the region in advance. However, at the very beginning, two agents attempt to approach to each other without considering the current location of the target because two agents are far away from each other at that time. After the agents are close enough to their nearest neighbor, they start to take the information of the location of the target into consideration and try to move towards the direction of the target. Therefore, the distances between two agents decrease at the beginning while the distances between Agent-2 and the target increase a bit at the beginning. As a result of the information of location of the target from the sensor networks, then the agents are able to move effectively towards the direction of the target and the distances between the agents and the target decrease extremely. However, at the time instant $t = 27$, the distances between the agents and the target increase a bit due to the avoidance of the agents. Finally, the target was captured by Agent-1 at position C at time $t = 30$ while Agent-2 located at position G1.

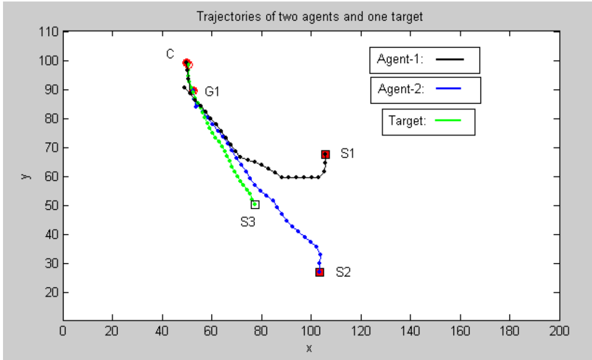

Fig.4. Trajectories of two agents and one target. Two agents start at positions S1 and S2 respectively while the target starts at position S3. The black, blue and green lines represent the trajectories of Agent-1, Agent-2 and Target respectively. The target was captured by Agent-1 at position C while Agent-2 was located at position G1.

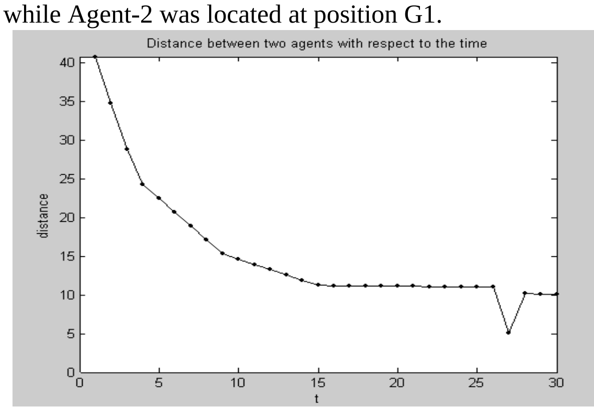

Fig.5. Distances between two agents with respect to the time.

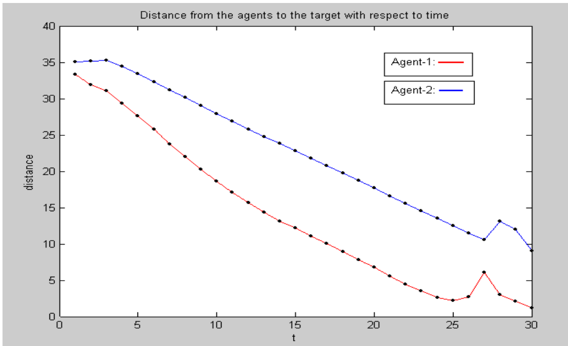

Fig.6. Distances from agents to the target with respect to

the time. The red line represents the distance from Agent-1 to the target while the blue line represents the distance from Agent-2 to the target with respect to the time.

Although only one agent finds the target, there is at least another agent who is capable of communicating with it. As a result, the situations in which the failure of the current agent happens and the target can not be further transported to a designated place by only one agent are able to be handled quickly and efficiently. At this moment, Agent-2 is able to replace or assist Agent-1 to carry out the task of transporting the target immediately. The corresponding response time is determined by the traveling time from the current location of Agent-2 to that of the target. Because of the local interaction and local decisions, the task can be responded quickly and efficiently. Fig.7 shows the comparative results of the response time obtained by the coordination algorithm proposed in this paper and the centralized coordination algorithm. The response time for the coordination algorithm proposed in this paper is about twenty-five percent of that for the centralized algorithm. So the coordination algorithm proposed in this paper is able to greatly reduce the time of further operation on the target such as capturing the target. (Note: the response time for the centralized coordination algorithm is equal to the traveling time from the current location of an agent located randomly in the region to that of the target).

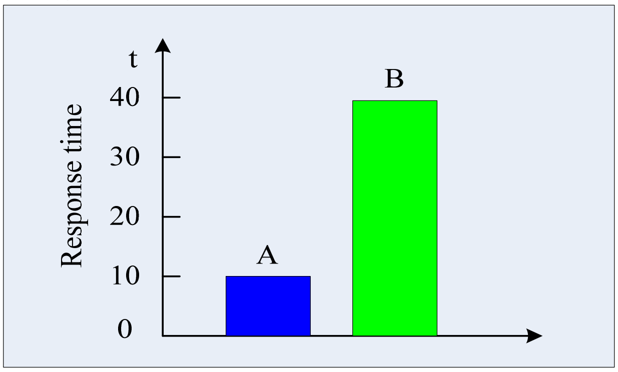

Fig.7. Response time of transporting the target with the coordination algorithm proposed in this paper and the centralized coordination algorithm. A denotes the coordination algorithm proposed in this paper while B denotes the centralized coordination algorithm.

Basically, the improved performance is attributed to the information of the target provided by the sensor networks deployed in the interested region in advance. By achieving the location of the target at the current time, agents are able to move towards the directions of the target in purpose. As a result, the time of chasing and capturing the target is able to be reduced greatly. However, in the situation without sensor networks, the information of the target is achieved only by sensors equipped on agents themselves. The local sensing range limits the efficiency of chasing and capturing the target. So the time of chasing and capturing the target is always larger than that in the situation without sensor networks. In the simulation below, the sensing range of agents is assumed to be a disk with the radius r centered at the agents. Agents can make effective decisions when the target is within the sensing range of agents or when the target is found by any agent. The time of chasing and capturing the target without the help of sensor networks (black line) changes with respect to the sensing range of agents, but the time with sensor networks (red line) is irrelevant with the sensing range r because the information of the target is provided by sensor networks.

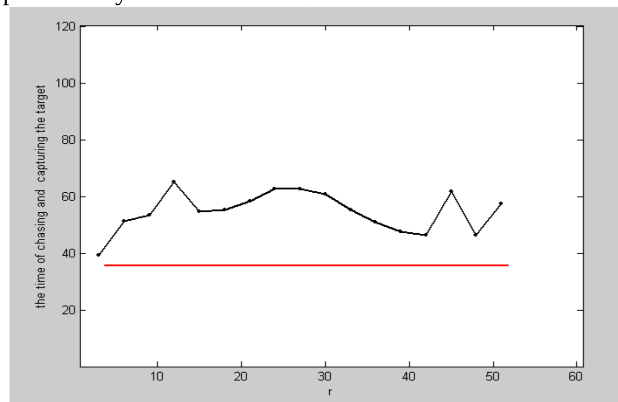

Fig.8. The time of chasing and capturing the target with the coordination algorithm proposed in this paper and the centralized coordination algorithm. The red line denotes the time produced by the coordination algorithm proposed in this paper. The black line denotes the time produced by the centralized coordination algorithm. Here the horizontal axis r denotes the sensing range of the agents.

The advantages of deploying sensors in the interested region are very clear according to simulations mentioned above. Sensor networks can provide global information due to the spatial distribution of sensor nodes in the interested region. Based on the information, many tasks such as chasing and capturing one or more targets are able to be finished more effectively. Along with the cost reduction of the sensor nodes, sensor networks will become an infrastructure in many applications.

VI. CONCLUSIONS AND FUTURE WORK

This paper examines the problem of coordinating multiple agents in chasing and capturing single mobile target with the aid of sensor networks. Also a probability-based algorithm is proposed to reduce the time of chasing and capturing the target. In the algorithm, we have taken the constraints of the non-deterministic sensing information obtained from sensor nodes and the limited communication range of agents into consideration. The sensing information is described with a probabilistic row vector, the elements of which are calculated according to the signal-strength received by each node. The limited communication range of agents is handled by maintaining the agents within a mobile network. In addition to reducing the time of capturing the target, the algorithm proposed can also keep the consistency of the location information of the target and improve the robustness of the capture when any agent is able to break down.

For the future work, first of all, we intend to extend the coordination algorithm proposed to work in more complex environments, for example, the environment with static obstacles. Secondly, we plan to consider the methods of splitting the large agent network where many agents are involved in the same network. Last but not least, we are going to investigate the methods of how to allocate tasks when a large number of targets are needed to chase and capture.

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