An aggregating approach of target enclosure of robot swarm

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***Abstract*—This paper presents a robot swarm model to enclose a target. The robots use information of the target and their each neighbors. Every robots have a own but same torch like signal emitter and they can observe the sum of the intensity of their torches. In this paper, the robot uses a direction with strongest intensity of the emitter as direction of its nearest neighbor. We expect that this new approach makes the robot swarm more simple and scalable. We confirm this model by computer simulations.**

I. INTRODUCTION

In this paper, a new implementation of a robot swarm for enclosing a target is examined. The swarm employs a same limited transmission range signal emitter. We suppose that this communication system makes a large swarm be built more easier.

Target enclosure task, which is useful for monitoring disaster sites and unknown vehicles, has recently become an important goal for multiple robots. Robots can operate in dangerous circumstances, replacing human presence.

These sites are usually far from where its operator is. It happens that the group of robots notices the fact of the exact number of sites to be observed and their location. Therefore, it is desirable that the larger number of robots than the necessary size is employed. At least, it will accept the large number of targets than their expectation.

We focused on the study of Takayama et al.[**?**]. In this model, each robot needs information of directions to one neighbor and to its target. As in other studies, this model also requires the Hamiltonian cycle constraint[**?**][**?**].

Recently, research[**?**] uses hybrid system theory[**?**][**?**] and shows robots controlled by Takayama's work referencing nearest neighbors can also enclose a target. The robot swarm with this new reference model can enclose targets while the size of group is changing[**?**].

Scalability is one of important properties of a robotic swarm. Although this target enclosing algorithm has this ability, the accurate observation of the neighborhood usually becomes difficult as the number of robot increases.

For example, ways to know who is a nearest neighboring robot can be enumerated as follows. (1) every robot has its unique signal emitter. and a receiver measures the power of the incoming signals. (2) each robot observes its neighborhood visually and measures the size of robots. These 2 methods are based on relative distance among robots. (3) each robot calculates own location on a common reference frame. The information of the robot's location are exchanged by broadcasting. The first method is stable but the number of robot is limited. The second method is reasonable but the visibility is strongly influenced by environment condition. The third method is the best way when we can use GPS and a wireless communication network.

We focus on a system with limited range homogeneous signal emitter. We call it torch system. For example, Kilobot[**?**] has a same small LED emitter as a communication device and a flock of 1000 kilobots can form a large shape. However, the transmission range of their LED light is about 6 robot length. Swarmbot[**?**] proposes that the robot having a homogeneous light can collect the sufficient number of robots to solve a task. Each robot has same color lights around its body. The intensity of light becomes strong as robots increase. If the intensity of light is too strong a robot will not join the group.

Advantage of this torch system is its high procurability. The very limited transmission range provides less interference of communication. Therefore, emitters which use same signal band can be installed into many robots. Also, its small energy consumption is also an advantage. The more smaller range communication only needs smaller energy consumption.

In this paper, we examine an robotic swarm with torch system for the target enclosing task. We adopt Takayama's work for the control scheme of robot but the referencing robot is different to this work. We propose that a most powerful signal direction is used as the direction of the referencing robot. We call this direction "MOPS" direction. In this paper, we show the proposed robotic swarm can enclose a target successfully by computer simulation.

This paper is composed as follows. Firstly, Takayama's work is introduced. Next, the proposed method based on

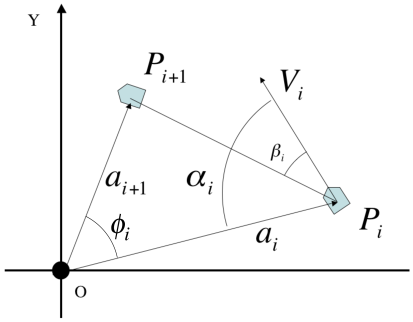

Fig. 1. Model of Takyama's enclosing a target algorithm: α, β.

MOPS is shown. In the third section, communication protocols are proposed. In this section, we show one of the protocols has reasonable scalability for this robotic swarm. Then, by the computer simulations, we show the ability of the target enclosing task of the proposed system.

II. TAKAYAMA'S TARGET ENCLOSING MODEL

Firstly, Takayama's target enclosing model is explained.

We assume that all robots choose the same target. We assume that on a two-dimensional (2D) plane, there is only one target O at the origin and n robots. Robots are numbered counterclockwise as $P_1, \ldots, P_n$, and r_i is the position vector of the robot P_i.

To achieve this task, Takayama et al.[**?**] proposed the following model. Each robot determines its control input, speed v_i, and angular velocity ω_i using two aspects of angular information: relative angles with respect to the target and an anterior neighboring robot,denoted as α_i and β_i, respectively. As a result, rotational movement occurs with a central focus on the target.

$$v_i = f\beta_i \tag{1}$$

$$\omega_i = v_i/\bar{r} - k\cos\alpha_i \tag{2}$$

where the parameters $\bar{r}, k$, and $f > 0$ specified beforehand. P_{i+1} is the robot to which P_i refers, and $\bar{r}$ is the expected distance to the target. In Takayama et al.'s model, the i-th robot refers to the $i+1$-th robot, and the n-th robot refers to the first robot P_1. That is, if the relationship between a robot and its reference robot is considered as a link in graph theory, the graph of the group of robots must be a Hamiltonian cycle. The authors proved the convergence to the goal state of the target enclosing task under this constraint.

A. Nearest neighboring robot as the reference

[**?**] examined a new reference robot scheme in which each robot considers its nearest neighboring robot as its reference robot. Each robot controls itself as described in equations **??** and **??**, but it chooses its nearest neighbor as its reference robot. This system has higher scalability because individual robots need not be identified to observe the nearest robot.

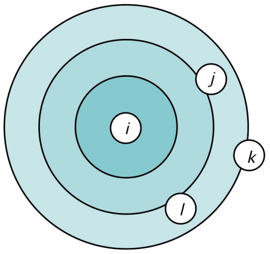

Fig. 2. Diffusion of light of torch

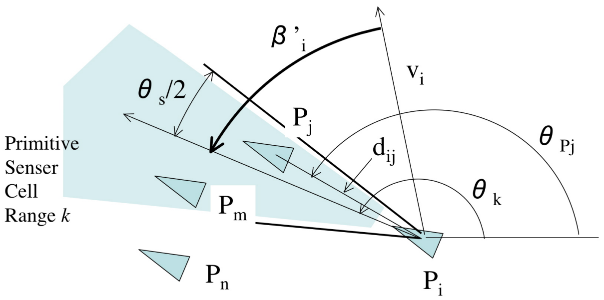

Fig. 3. The most powerful signal(MOPS) direction

III. THE PROPOSED REFERENCE MODEL: THE MOST POWERFUL SIGNAL DIRECTION REFERENCE MODEL,MOPS MODEL

We propose a new robotic swarm for the taget enclosure task. Each robot has the own but same specification torch. Additionally we propose a most powerful direction of their signal is used as the direction of the referencing robot. First, we explain the torch which the robot has.

A. Torch

Every agent has a same torch and it can turn on/off its torch. The maximum intensity of all the torch is same and known beforehand. We suppose that the speed of propagation of the signal of the torch is so fast that an agent can observe the signal immediately.As shown in Fig.**??**, during the flight of the signal, the power of the signal is attenuated. The signal propagation function $p(d)$ is described as follows.

$$p(d) = \begin{cases} \frac{\gamma^{(d/L)}}{(d/L)^2} & d > L \\ 1 & (otherwise) \end{cases} \tag{3}$$

where d is the distance from the emitter, L is the length of an agent, γ is the attenuation coefficient per L. The equation **??** represents the spherical diffusion of a light. An agent closer to an emitter receives more stronger signal.

B. target enclosing model with MOPS direction reference model

We explain procedure of receiving signal of the proposed method. Agent P_i uses the most powerful signal direction

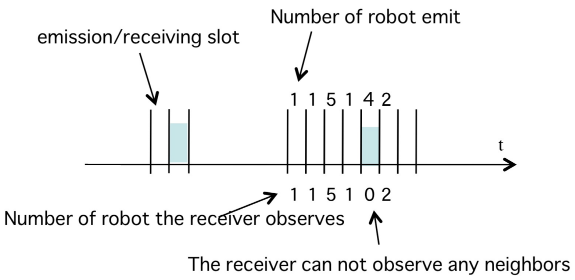

Fig. 4. The number of signal which a robot can receive

instead of the angle from P_i to $P_j(=\beta_i)$. Also, we call the angle β_i'. Fig.**??** shows this angle. Now, we suppose agent P_i has several signal receivers. We call it *sensor primitive*. The direction of k-th sensor primitive sp_k is θ_k. If $|\theta_k - \theta_{ij}| \leq \theta_s/2$, the sensor primitive sp_k can sense the signal of P_j. We call θ_s a visible range of sensor primitive.

The power of sensor primitive sp_k, s_k is

$$s_k = \sum_{P_m \in visible} p(d_{i,m}) \tag{4}$$

where $d_{i,m}$ is the distance between P_m and P_i and p is the signal propagation function in eq.**??**. β_i' is the substitution of β_i.

$$\beta_i' = \angle v_i O \theta_{\underset{k}{arg-max}\, s_k} \tag{5}$$

IV. TORCH FLASHING SIGNAL STRATEGY

In this section, we propose several torch flashing strategies and evaluate them by computer simulation. We show the high performance of protocol B which can collects sufficient information about neighbor agents.

Generally, an agent cannot observe its neighborhood when its torch is turned on because the power of own torch is too strong. This is a kind of dilemma. An agent should turn its torch on to notify other agents its existence. However, an agent should turn its torch off to know existence of other agents. Therefore, some reasonable torch flashing signal strategies are required.

We examine the following 5 strategies.(A) turn on with probability r and stop after the lapse of a fixed predetermined seconds(we call this strategy random_start+fixed_output_span). (B) turn on when someone starts and stop with probability r(reactive+random_stop)[**?**]. (C) turn on when someone starts and stop after the lapse of a fixed predetermined seconds (reactive+minimum_span).(D)turn its torch on always and take a break with fixed timing(greedy_fixed_output_span). (E)turn its torch on always and take a break with probability r(greedy_random_stop).

The criteria of the performance of protocol is the average of the number of signals recognized per interval on which an agent emits. We call this interval *slot*.Fig.**??** illustrates an example of emission and signal receiving process of an agent.All agents turn their own torches on or off according to the slot. The numbers above the line represent the number of agents which turn their torch on at each slot. If an agent turns its torch off, the agent can collect correct information of these agents. The number of information of agents which the agent can collect is shown below the line. The performance of protocol x, $eval_x$ is the average of these, namely,

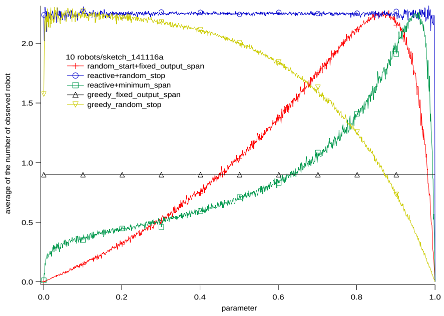

Fig. 5. The performance of the 5 proposed strategies (10 agents)

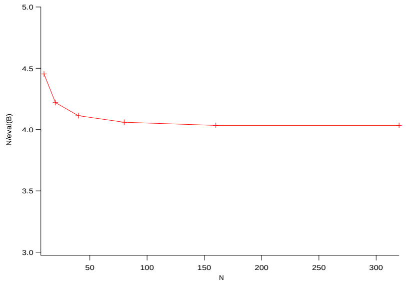

Fig. 6. The performance of strategy B according with the number of agents.

$$eval_x = \frac{\sum_{i \in N} \frac{\sum_{s \in S} receive(s,i)}{|S|}}{|N|} \tag{6}$$

$$receive(s,i) = \begin{cases} 0 & i \in Emit(s) \\ |Emit(s)| & (otherwise) \end{cases} \tag{7}$$

where $Emit(s)$ is a set of agents who their torches are on during slot s.

Fig.**??** shows the performance of the 5 strategies in the case of a group of 10 agents by computer simulation. The x axis indicates the parameter r and the y axis shows $eval_x$. Strategy B is better than other. This strategy can provide average 2.24 agents' information. This suggests that an agent with strategy B can collect information of all agents during 5 slots >10/2.24.

Fig.**??** shows $|N|/eval(B)$ of strategy B. $|N|/eval(B)$ is the average number of slots which a robot required to collect information of all agents. As this graph indicates, $|N|/eval(B)$ is almost flat and it shows the agent can collect all members' information during the fixed time span despite of swarm size $|N|$.

The above experiment, the agent with strategy B can collect sufficient information to do the target enclosing task in a constant time span. In the next section, we show the result of target enclosing by computer simulation.

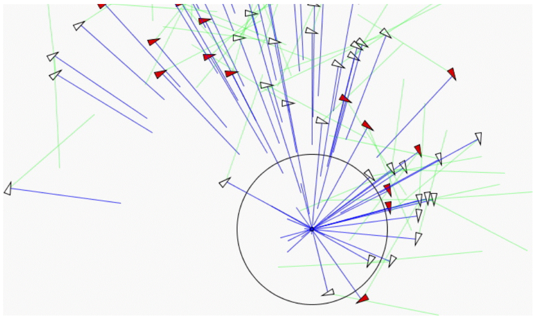

Fig. 7. An example of initial state of taget enclosure with 60 agents

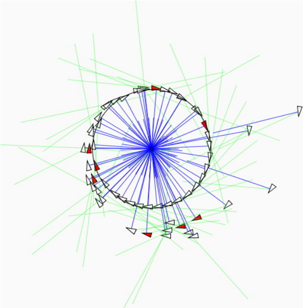

Fig. 8. An example of near completion of taget enclosure with 60 agents

V. COMPUTER SIMULATION

In this section, the result of computer simulation of enclosing a target by a robot swarm with the proposed MOPS direction reference model (eq.**??**) is shown.

The setting of experiment is explained. There is 1 target at the origin. There are $|N|$ agent which are deployed at random far from the origin. We suppose that the agents use strategy B and every agent can receive signal of torch of all agents.

Examples of process of enclosing the target are shown by Fig.**??**,**??**. In this case, we set that $|N| = 60$ and the attenuation coefficient $\gamma = 0.9999$. The circle indicates the orbit on which agents enclose the target. A triangle indicates an agent. The 2 lines from each triangle represent its target and the direction $\beta'_i -$. If the gap between $\beta'_i -$ and the direction to its nearest neighbor agent is large, namely ($|\beta'_i - \beta_i| > \theta_s$), the triangle is filled. As you see In Fig.**??**, the agents can enclose the target and according with the increase of the number of the agents on this orbit, the number of the filled triangle becomes small.

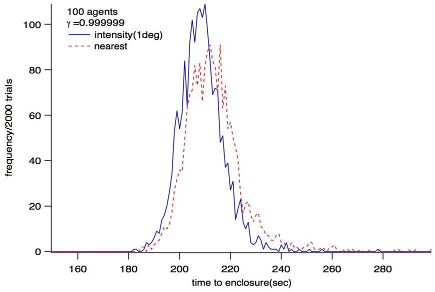

Fig. 9. Histogram of time to enclose a target by 100 agents.2000 trials are examined.

We repeated 2000 times this attempt to enclose the target. The group size $|N|$ is 100. At every attempt the agents started from different positions. All the attempts succeeded. Fig.**??** shows the histogram of time to enclose the target.

VI. CONCLUSION

In this paper, a new implementation of a robot swarm for enclosing a target is examined. The swarm employs a same limited transmission range signal emitter. Every robots have a own but same specification torch and they can observe the sum of the intensity of light of their torches. The robot uses the direction with strongest intensity of the light which is an alternative to direction to its nearest neighbor agent. We proposed the scalable torch flashing strategy and the performance of them was evaluated. By the computer simulation, we confirmed that the proposed system can enclose a target.

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