Swarm Robots Using A New Lévy Walk Generator in Targets Exploration

Yoshiaki Katada[1]

Setsunan University, Osaka, Japan,
katada @ setsunan.ac.jp,
WWW home page: http://www.setsunan.ac.jp/~katada/

Abstract. This study tackles the task for swarm robotics where robots explore the environment to detect many targets. When a robot detects a target, the robot must be connected with a base station via intermediate relay robots for wireless communication. In our previous results, we confirmed that Lévy walk outperformed the usual random walk for exploration strategy in real robot experiments. This paper investigated the performance of a new Lévy walk generator, which is recently proposed in biology, for the targets exploration problem on robotics through a series of computer simulations and compared the performance with those for the Lévy walk generator employed in our previous work. The results suggest that the search of the new Lévy walk is robust for uniformly and non-uniformly distributed targets and outperforms the previous one.

Keywords: swarm robotics, Lévy walk, navigation, mobile robots

1 Introduction

Swarm Robotics (SR) [1–3] have attracted much research interest in recent years. Generally, the tasks in SR are difficult or inefficient for a single robot to cope with. Thus, you find overlap between SR and multi-robot systems. Şahin [4] enumerated several criteria[1] for distinguishing swarm robotics as follows; Autonomy: Each robot should be physically embodied and situated. Redundancy: Group sizes accepted as swarms is 10 to 20. Scalability: SR system should be able to operate under a wide range of group sizes. Simplicity: Each robot should employ cheap design, that is, the structure of a robot would be simple and also the cost of it would be cheap. Homogeneity: SR system should be composed of homogeneous individuals. This enhances the above 2nd and 3rd criterion. According to the last criterion, homogeneous controllers for individuals are desirable for SR systems. Additionally, this approach does not assume the existence of an explicit leader in swarm robots due to the above criteria. This results in that a collective behavior emerges from the local interactions among robots and between the robots and the environment. Therefore, it is required for SR systems

[1] Şahin [4] claimed that these criteria should be used as a measure of the degree of SR in a particular study.

that individuals in swarm show various behaviors through interactions although the individuals are homogeneous.

The typical control tasks in SR are navigation, aggregation, formation, transport, and decision-making, requiring distributed collective strategies [2, 7]. In this paper, we copes with a target detection problem, which is one of navigation problems. In this control task, several robots can communicate with each other via wireless communication networks (WCN) [5, 6] due to the multi-hop transmission to achieve collective exploration. As soon as a robot detects a target, the information is sent from the robot to the base station via intermediate relay robots. Therefore, all robots should be "connected" to the base station via WCN.

Our research group investigated communication range and the number of robots required for a SR network to achieve connectivity based on percolation theory in computer simulation [8]. According to the results obtained in [8], we conducted a series of real experiments [9]. Also, we must consider the performance of exploration as well as connectivity of the SR network in a target detection problem. Therefore, we improve exploration strategies to enhance the performance.

In a target detection problem which we cope with, we assume that robots have no prior knowledge of the environment. In these scenarios, a random walk seems to be appropriate for exploration strategy. It has been reported in the literature [10, 11] that some species show a specific random walk, Lévy walk [12], when prey are sparsely and randomly distributed. This condition might correspond to a target detection problem. In our previous works[13], we conducted a series of real experiments on a target detection problem by swarm robotic network in order to investigate the effect of the step size of the random walk and the number of robots. We confirmed that Lévy walk outperformed the usual random walk for exploration strategy in real robot experiments. In computer simulation [14], we investigated which probability distribution for Lévy walk shows best performance in a many targets detection problem varying its parameters and confirmed that the probability distribution which adopted in [13] was best. Lévy walk is often discussed based on probability distribution in literature. Recently, Abe [15] proposed a new Lévy walk model based on nonlinear dynamics, and observed the movement trajectories of a species of animal, and then found out that those are consistent with his model.

This paper investigated the search performance of a Lévy walk generator based on nonlinear dynamics in a many targets detection problem varying the parameters for experimental setting and compared the performance with those obtained in our previous work through a series of computer simulations. The paper is organized as follows. The next section explains the two kinds of Lévy walk. Sect. 3 shows the structure of the simulated mobile robots. Sect. 4 describes the controller of the robots and how to implement Lévy walk in the controller, respectively. Sect. 5 conducts a series of computer simulations in order to investigate the performance of the two kinds of Lévy walk. Conclusions are given in the last section.

2 Lévy Walk

A random walk with a constant step size is well known as Brownian walks. On the other hand, Lévy walk is a random walk whose step size varies according to a power-law distribution. This section introduces the two kinds of lévy walk generators employed in this study.

2.1 Lévy Walk Based On Probability

Lévy probability distribution [12] for a step size, w, is formulated as follows:

$$L_{\alpha,\gamma}(w) = \frac{1}{\pi}\int_0^\infty e^{-\gamma q^\alpha}\cos(wq)dq, \quad \gamma > 0,\ w \in R \tag{1}$$

where γ is the scaling factor and α $(0 < \alpha < 2)$ is a parameter varying the shape of the probability distribution.

Lévy probability distribution for a step size can be approximated in the following [16]:

$$L(w) \propto w^{-\alpha} \tag{2}$$

According to the recommendation in [13, 17], we define it as follows:

$$L(w) \equiv w^{-1.2} \tag{3}$$

Fig. 1 shows Equation (3) truncated over the range $1 \leq w \leq 30$. On the many targets detection problem[14], we compared the performance of Equation (3) with those of the other formulations of Lévy probability distribution through a series of computer simulations and confirmed that Equation (3) shows the best performance in the robot control problem. Thus, we employ Equation (3) as a Lévy walk based on probability distribution in this study.

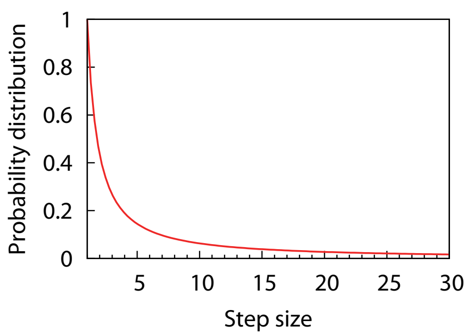


Fig. 1. Lévy probability distribution

2.2 Lévy Walk Based On Nonlinear Dynamics

Recently, Abe [15] developed a model of simple, deterministic, and nonlinear system where Lévy walks emerging near a critical point, and discussed its characteristics relating to biological systems. This model is attractive from the robotics point of view because it would be easy to implement it for a mobile robot for the following reasons;

- The process for generation of Lévy walk is deterministic, except that only the initial states are randomly determined. We do not have to implement any probability distribution for Lévy walk although it is sometimes hard to write a source code with it.
- The computational cost is low for generation of Lévy walk.
- The physical meaning of the model is interpretable for mobile robot locomotion. This is mentioned later.
- The move phase and rotate phase go together. This can be easily implemented and does not require any control unit.

The mathematical formulation is as follows;

The nonlinear system has two internal states, $x_t, y_t \in [0, 1]$. These internal states are updated in the following way:

$$x_{t+1} = (1 - \epsilon)f(x_t) + \epsilon f(y_t) \tag{4}$$

$$y_{t+1} = (1 - \epsilon)f(y_t) + \epsilon f(x_t), \tag{5}$$

where $\epsilon \in [0.0, 0.5]$ is the coupling strength between x and y, and f is a nonlinear function.

A tent map was employed as the nonlinear function f in [15].

$$f(x) = \begin{cases} x/r & (x < r) \\ (1 - x)/(1 - r) & (x \geq r), \end{cases}$$

where r is a parameter of the tent map. An agent movement is determined by the above internal states as follows;

$$\Delta\theta = c(x_t - y_t) \tag{6}$$

$$\theta_{t+1} = \theta_t + \Delta\theta \tag{7}$$

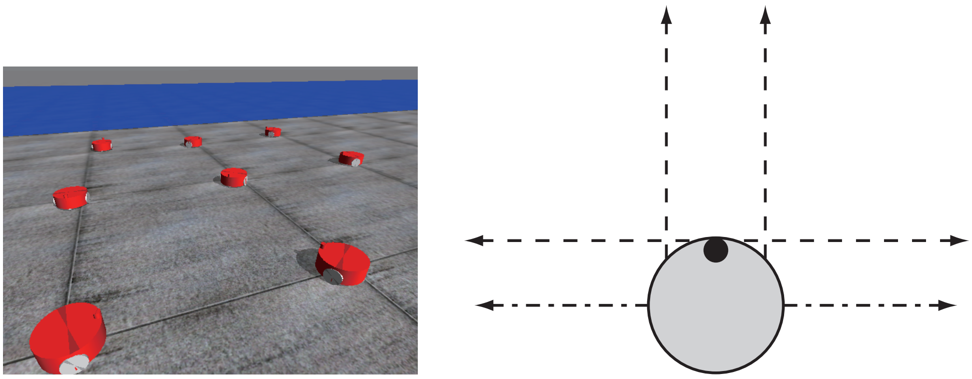
$$X_{t+1} = X_t + \cos\theta_t \tag{8}$$

$$Y_{t+1} = Y_t + \sin\theta_t, \tag{9}$$

where, c is set to $\pi / \max|x_t - y_t|$, and θ, X and Y are the orientation and position of the agent. Thus, the speed of the agent is 1 per time step. The reference [15] reported that the dynamics of Equation (7) change drastically with the parameter, ϵ; The dynamics shows a Brownian random walk when ϵ is small, Lévy walk when ϵ is near a critical point, and constantly straight movement when ϵ is above the critical point. At a critical point, $\epsilon = 0.22$ when $r = 0.7$.

3 Simulated swarm robot and environment

According to our previous work using the swarm mobile robots [13], the setting of computer simulations was as follows. Differential wheeled robots (Fig. 2(a)) were used in this experiment. The robot's diameter and height are 0.17 [m] and 0.075 [m], respectively. The robot is equipped with four distance sensors located at the front of the body for measuring the distance to other robots and walls, and two sensors located at both ends of the body for detecting targets (Fig. 2(b)). The maximum detection ranges of the former distance sensor and the latter sensor are 0.3 [m] and 0.2 [m], respectively. The robots are assumed to be equipped with wireless devices, which can compose wireless ad hoc networks and communicate with each other via multi-hop path.



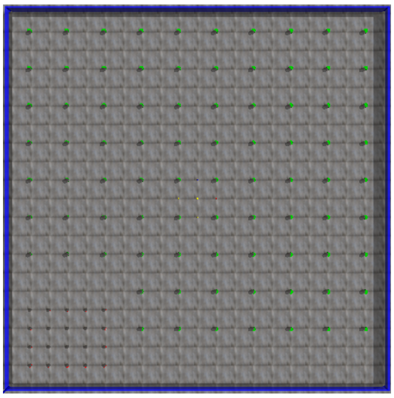
(a) Differential wheeled robots

(b) Ray of the distance sensors (dash line) and the target detection sensors (dot-dash line)

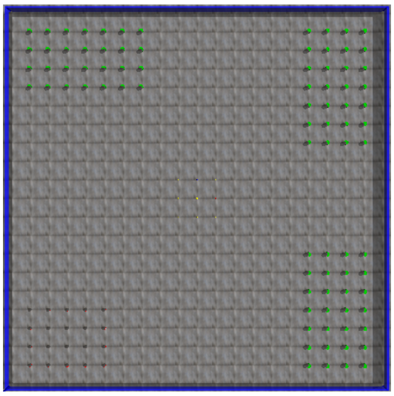
Fig. 2. Set up for computer simulation: swarm robot

The simulated environment is a square arena with walls (Fig. 3). The length of the wall was set to 20 [m]. At the lower left corner, a wireless base station was placed. The communication range of the wireless device was set to 20 [m]. The connectivity of the wireless communication network is checked based on geometric model [6, 8]. At the beginning of each trial, swarm robots were always placed 1 [m] apart at the same initial position, the lower left corner, next to the base station at random orientations (Fig. 3(e)). The cylindrical objects were placed as targets. The radius of the cylinder is 0.11 [m] and the height is 0.22 [m]. Targets were uniformly or non-uniformly distributed over the arena. The number of targets was set at $T \in \{84, 168, 336\}$.

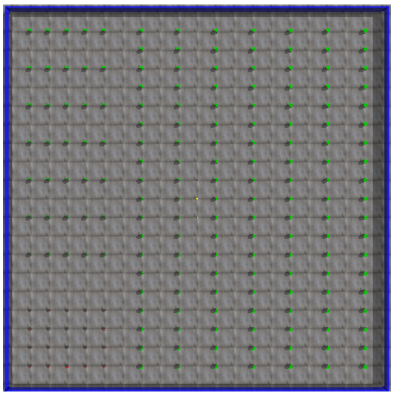
Open Dynamics Engine (ODE) [18] was employed in order to consider dynamics of robots and the interaction between robots and environment.



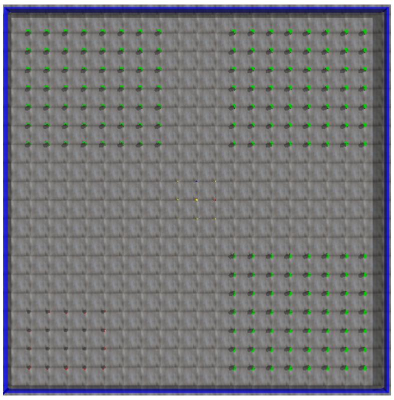
(a) $T = 84$, *uniform*



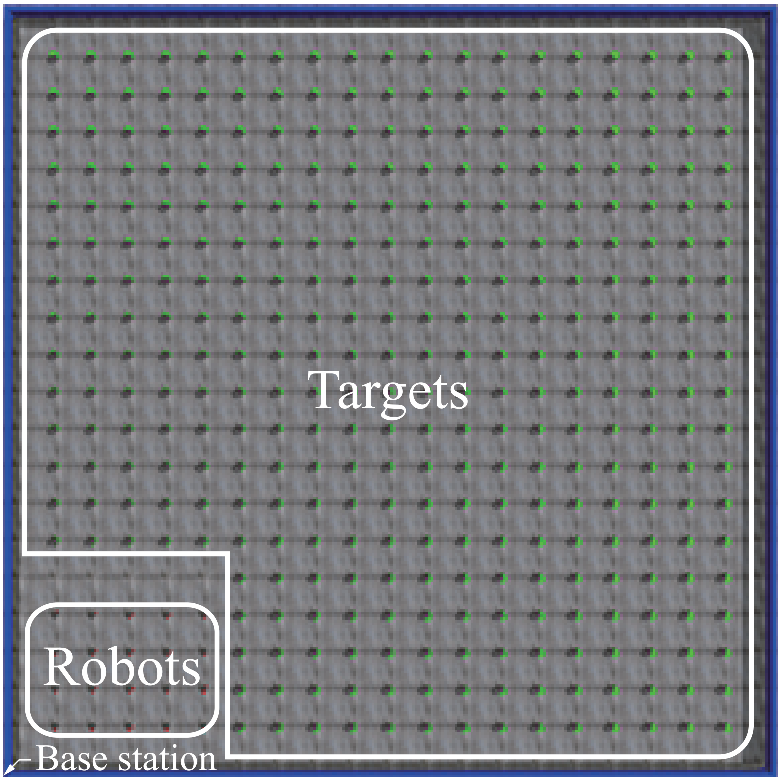
(b) $T = 84$, *non-uniform*



(c) $T = 168$, *uniform*



(d) $T = 168$, *non-uniform*



(e) $T = 336$, *uniform*

Fig. 3. Set up for computer simulation: distribution of targets

4 Controller

4.1 Subsumption Architecture

Subsumption architecture (SSA) [19] is employed as a format to describe individuals' behavior of the swarm robotic network according to the setting of our previous work [13]. Fig. 4 shows a layer structure of SSA implemented in this swarm robots. The SSA to achieve the control task in this study comprises the following three layers: *transmission*, *obstacle avoidance* and *target exploration*. A capital I in a circle in Fig. 4 indicates *inhibition* by which a lower layer is inhibited when an upper layer is activated. Each layer is composed of some modules connected to each other.

The behavior of each layer can be explained as follows. In the transmission layer, the *detect target* module sends messages to the *transmit messages* module and the *stop* module when the sensory inputs from the sensors for detecting targets are beyond a threshold. The *transmit messages* module transmits messages to the base station via intermediate relay robots. The *stop* module sends messages to its own motors to stop them. In the obstacle avoidance layer, the *detect obstacle* module sends messages to either *turn right* module or *turn left* module according to the sensory inputs from distance sensors described in Sect. 3, in order to avoid the obstacles which the robot faces. In the target exploration layer, Lévy walk (Sect. 2) is implemented. The details are described in the next subsection.

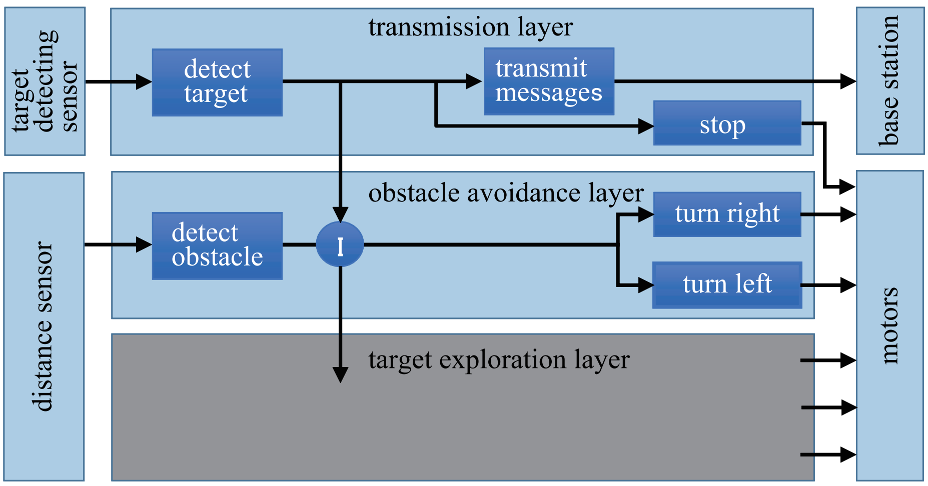


Fig. 4. Layer structure of SSA

4.2 Implementation of Lévy walk in the SSA

Lévy Walk Based On Nonlinear Dynamics (LW_{nd}) Lévy walk based on nonlinear dynamics can be easily implemented as mentioned in Sect.2.2, especially for the differential wheeled robots. In the model of the differential wheeled robots based on ODE (Sect.3), the angular velocities of the wheels are controlled for behavior control. Therefore, the angular velocities are determined as follows;

$$v_r = \omega_{max} \cdot x \tag{10}$$

$$v_l = \omega_{max} \cdot y, \tag{11}$$

where v_r and v_l are the angular velocities for right and left wheels, ω_{max} is the maximum angular velocity of the wheel, and x, y are determined according to Equations (4) and (5), respectively. This leads the orientation of a robot on kinematics, which is identified with Equation (6). Therefore, the trajectories would follow the dynamics of Equations (7)-(9) without the calculation of Equation (6). The internal states (Equation(4)(5)) are updated every 0.5 [s]. The target exploration layer for Lévy walk based on nonlinear dynamics can be described in Fig. 5.

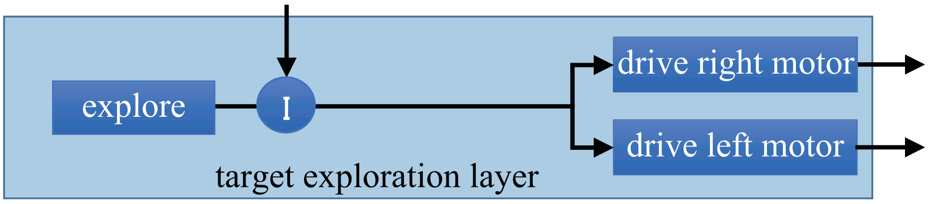


Fig. 5. Details of the target exploration layer for LW_{nd}

Lévy Walk Based On Probability (LW_{prob}) In the target exploration layer for Lévy walk based on probability described in Sect. 2.1, the *explore* module sends messages to one of the following three modules: *forward*, *turn right* and *turn left*, where *forward* means moving forward and *turn right* (*left*) rotating clockwise (counter clockwise) at the position (Fig.6). In each module, the rotational direction of the right and left wheels are set, respectively. The angular velocity in the *forward* module is set at a constant value, which is the same as ω_{max} for LW_{nd}. The angular velocity in the *turn right* and *turn left* modules is set at 65 percent of ω_{max}.

For the differential wheeled robots assumed to be used in this study, it is difficult to simultaneously move forward with a regular step size and rotate in the predetermined direction. Therefore, the whole steps are divided into the rotation phase and the move-forward phase (Fig. 7). The transition between them occurs at 100%. In the rotation phase, a robot randomly determines the direction of rotation and randomly selects an angle of rotation from $\{45, 90, 135\}$ degree. Then, a robot rotates until reaches the desired angle (the *turn right* or *turn left* module in Fig. 4). In the move-forward phase, a robot moves forward driving two wheels (corresponding to the *forward* module in Fig. 4). The execution time in the move-forward phase is a random value w according to a Lévy probability distribution(Equation (3)) multiplied by w_0, where w_0 is the minimum movement time and set at 6 [s] according to the previous experiment [13].

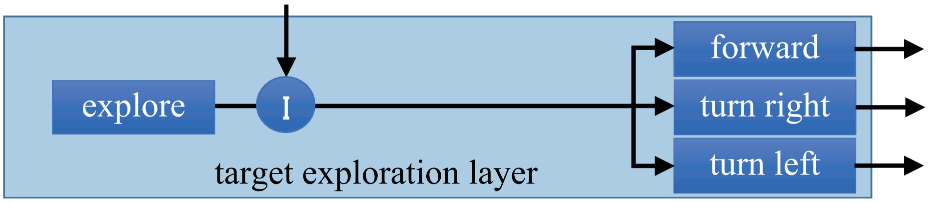


Fig. 6. Details of the target exploration layer for LW_{prob}

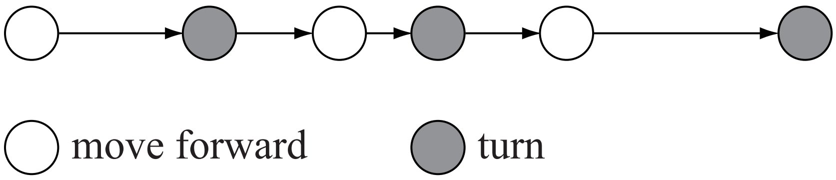


Fig. 7. Transition between move phase and rotate phase for LW_{prob}

5 Computer Simulation

5.1 Setting of computer simulations

A series of computer simulations have been conducted varying the number of robots $N \in \{5, 10, 15, 20\}$ and the target distribution described in Sect. 3. One trial ends when $360,000$ steps (3600 sec) are performed. This experiment investigated the performance of Lévy walks, LW_{nd} and LW_{prob} described in Sect.4, formulating target detection rate as $T(t)/T$, where $T(t)$ is the number of targets detected by swarm robots at t time step. We conducted 50 independent runs varying the initial orientations of the robots. All results were averaged over 50 runs.

5.2 Experimental results

Fig. 8 shows the average detection rate at each time step for LW_{nd} and LW_{prob} with N and T, respectively. The final detection rate converged to 100 % for all the N except for $N = 5$. For LW_{nd}, no significant differences of the detection rate in the search process (we call this a search speed in the reminder of this paper) for each N were observed among the distribution of targets (Fig.8(a), 8(c), 8(e) and 8(g)). The speed becomes faster with the increase of N for each target distribution.

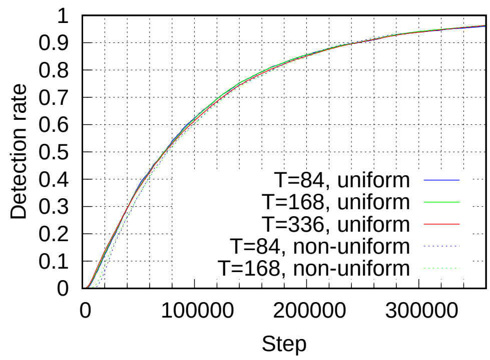
Meanwhile, the speeds for *non-uniform* were smaller than those for *uniform* for LW_{prob} for each N (Fig.8(b), 8(d), 8(f) and 8(h)). Increasing N had the same effect for the target distribution.

LW_{nd} outperformed LW_{prob} for each N, especially when targets were non-uniformly distributed. One reason for this would be that LW_{nd} does not divide the whole steps of movement into the rotation phase and the move-forward phase. The robots according to LW_{nd} always move.

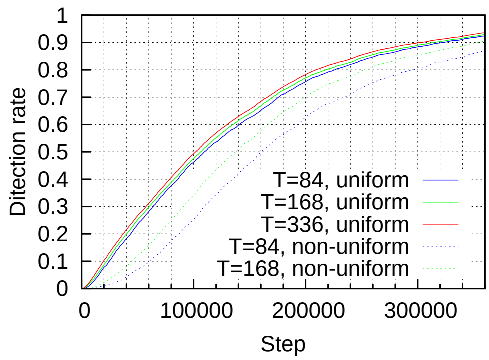
6 Conclusions

This paper investigated the search performance of the two kinds of Lévy walk in the many targets detection problem varying the number of robots and the target distribution through a series of computer simulations. The results suggest that LW_{nd} outperformed LW_{prob} in this experiment. LW_{nd} can generate Lévy walk without dividing the whole steps of movement into the rotation phase and the move-forward phase. Therefore, it is predictable that the search speed for LW_{nd} is faster than the one for LW_{prob}. Moreover, no significant differences of the speed for LW_{nd} were observed between for uniform target distributions and non-uniform ones. I cannot still figure out this reason.

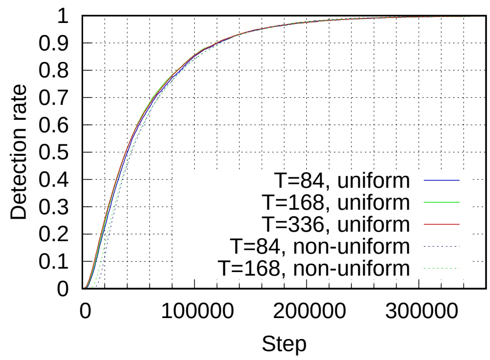
As I mentioned in Sect.2 and 3, LW_{nd} can be easily implemented for robotic control due to its mechanism. Future work will investigate the performance of Lévy walk based on nonlinear dynamics in real robot experiments.



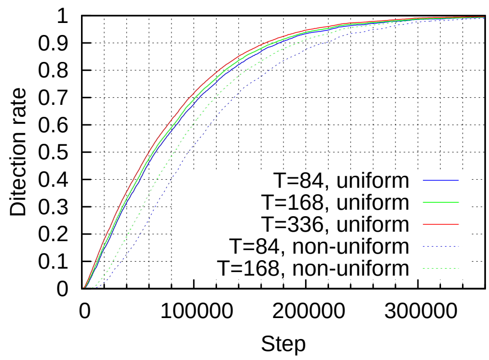
(a) LW_{nd} for $N = 5$



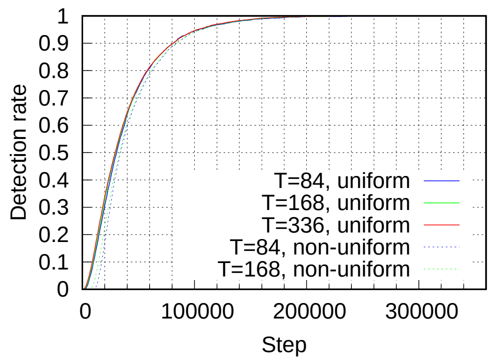
(b) LW_{prob} for $N = 5$



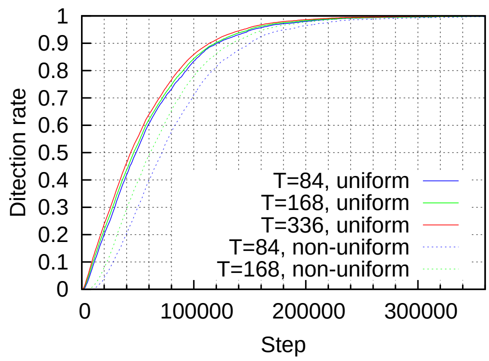
(c) LW_{nd} for $N = 10$



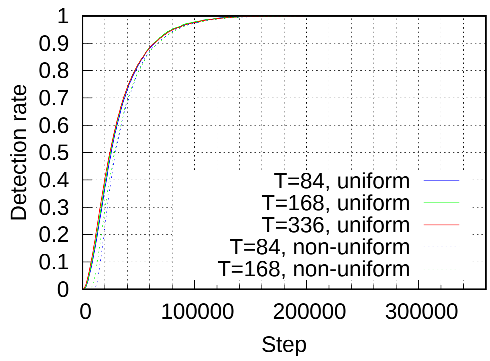
(d) LW_{prob} for $N = 10$



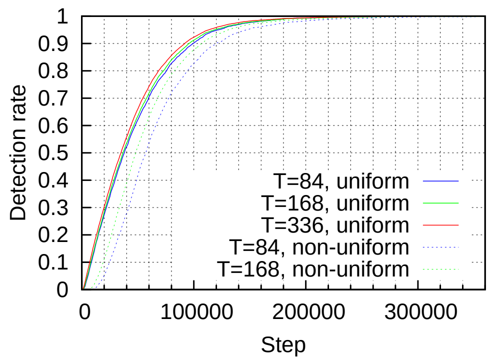
(e) LW_{nd} for $N = 15$



(f) LW_{prob} for $N = 15$



(g) LW_{nd} for $N = 20$



(h) LW_{prob} for $N = 20$

Fig. 8. Average detection rate for each time step

References

1. V. Trianni, *Evolutionary Swarm Robotics*, Springer-Verlag, 2008.
2. M. Brambilla, E. Ferrante, M. Birattari, M. Dorigo, “Swarm Robotics: A Review from the Swarm Engineering Perspective,” *Swarm Intelligence*, Vol.7, No.1, pp.1–41, 2013.
3. H. Hamann, *Swarm Robotics: A Formal Approach*, Springer, 2018.
4. E. Şahin, “Swarm Robotics: From Sources of Inspiration to Domains of Application,” Lecture Notes in Computer Science, Vol.3342, pp.10–20, 2005.
5. A. Ghosha, S. Das, “Coverage and Connectivity Issues in Wireless Sensor Networks: A Survey,” *Pervasive and Mobile Computing*, Vol.4, No.3, pp.303-334, 2008.
6. J. Li, L. Andrew, C. Foh, M. Zukerman, C. Hsiao-Hwa, “Connectivity, Coverage and Placement in Wireless Sensor Networks,” *Sensors*, Vol.9, No.10, pp.7664-7693, 2009.
7. L. Bayindir, “A review of swarm robotics tasks,” *Neurocomputing*, Vol. 172, pp.292–321, 2016.
8. Y. Katada, “Connectivity of Swarm Robot Networks for Communication Range and the Number of Robots Based on Percolation Theory”, *Proceedings of the 2014 IEEE/SICE International Symposium on System Integration*, pp. 93–98, 2014.
9. Y. Katada, K. Kogo, “Development of the Shortest Path Display System Using Swarm LED Indicators Based on Signal Strength of Wireless Communication”, *Proceedings of the 2017 IEEE/SICE International Symposium on System Integration*, 2017.
10. G. Viswanathan, V. Afanasyev, S. Buldyrev, E. Murphy, P. Prince, H. Stanley, “Lévy Flight Search Patterns of Wandering Albatrosses”, *Nature*, Vol.381, pp.413–415, 1996.
11. N. Humphries, H. Weimerskirch, N. Queiroz, E. Southall, D. Sims, “Foraging Success of Biological Lévy Flights Recorded in Situ”, *Proceedings of the National Academy of Sciences of the United States of America*, Vol.109, No.19, pp.7169–7174, 2012.
12. P. Lévy, *Theorie de l’Addition des Veriables Aleatoires*, Gauthier-Villars, 1937.
13. Y. Katada, A. Nishiguchi, K. Moriwaki, R. Watakabe, “Swarm Robotic Network Using Lévy Flight in Target Detection Problem”, *Artificial Life and Robotics*, Vol.21, No.3, pp.295–301, 2016.
14. Y. Katada, “Swarm Robotic Network Using Lv́y Flight for Exploration –Computer Simulation for Sweeping”, *Transactions of the Society of Instrument and Control Engineers*, Vol.54, No.1, pp.22–30, 2018 (Japanese).
15. M. Abe, “Functional Advantages of Lévy Walks Emerging near A Critical Point”, *Proceedings of the National Academy of Sciences, National Academy of Sciences*, 117(39), pp.24336–24344, 2020.
16. C-Y. Lee, X. Yao, “Evolutionary Programming Using Mutations Based on the Lévy Probability Distribution”, *IEEE Transactions on Evolutionary Computation*, Vol. 8, pp. 1–13, 2004.
17. H. Koyama, A. Namatame, “Comparison of Efficiency of Random Walk Based Search And Levy Flight Search”, *Information Processing Society of Japan*, Technical Reports (20), pp. 19–24, 2008 (in Japanese).
18. Open Dynamics Engine (ODE), “http://ode.org/”
19. R. Brooks, “A Robust Layered Control System for a Mobile Robot”, *IEEE Journal of Robotics and Automation*, Vol.2, No.1, pp.14–23, 1986.