Enhancing the capture efficiency of a micro-robotic swarm in targeted delivery using velocity control*

Akshatha Jagadish[1] and Manoj Varma[2]

***Abstract*— Swarm robotics at the micro scale is one of the popular research areas currently. However, there has been no generic approach to modelling, designing and controlling these micro-robotic swarms. In this paper, we investigate the capture efficiency of a micro-robotic swarm for the specific application of targeted delivery. We mathematically model the natural dynamics of the swarm that would help us understand the inherent passive behaviour of the swarm system. This would lead to optimal design and control of the micro-bots. We also investigate the effect of the mean control of the swarm on the capture efficiency η, which describes the efficiency of the micro-robotic swarm in reaching the target.**

I. INTRODUCTION

Micro-robotic swarm system research is ubiquitous in the field of engineering and science, where the former investigates the techniques to control the system for various applications such as manufacturing, delivery, surveillance, foraging and many more; and the latter studies the behavior of natural swarms that aids in understanding swarm intelligence and effectively apply the discoveries to swarm robotic systems. Here, we combine the two techniques to initially study the behaviour of the swarm and then apply control to improve the natural efficiency of the swarm system.

In our literature survey, we understood that there has been research going on to effectively control a swarm of robots in specific environments [1], and for specific tasks such as steering the swarm for obstacle avoidance [2]. This assumes a bit of computation and communication possible at the individual level and hence are applicable to macro-scale systems. This assumption fails at the micro-scale. There has been a lot of research into the design and development of different micro-robotic structures with minimal actuation [3] [4]. The control techniques at this scale is again different from that of macro-scale because there is uncertainty in the sensing and individual control of these particle-size microbots. The best approximation for such an uncertain motion of small particles is Brownian motion [5].

Brownian motion is mathematically modelled by a stochastic process called the random walk. We adopt this model to calculate the capture efficiency, η at the target. The target is absorbing in nature, meaning that, the bots reaching the target get stuck there.

This paper is organized as follows. Section II describes the system specifications, section III describes the mathematical model used to understand the swarm behaviour, section IV investigates two control techniques and their effects, section V gives the conclusion of this paper.

II. SYSTEM SPECIFICATIONS

A. System setup

The goal of the micro-robotic swarm is to reach a well-defined target area from the point of initiation. There are no boundaries of any kind in the environment. Fig. (1) shows the setup for a 2-D environment.

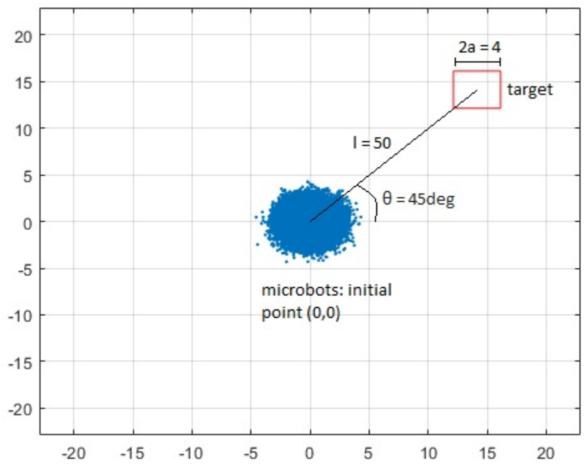

Fig. 1. Environmental setup with bots at the initial point

B. System parameters

The various parameters of the system with their corresponding units in SI system are defined as follows

- Diffusion co-efficient of the robotic swarm (D): m^2/s
- Distance between target and initial point (l): m
- Orientation of the target with respect to the initial point(θ): $radian$
- Size of target (a): m
- Time from initiation (t): s

III. MATHEMATICAL MODEL

Random walk in a 2-D environment results in a Gaussian distribution of particles in each dimension with mean as the initial point and standard deviation of $\sqrt{2Dt}$, the diffusion length for a given diffusion coefficient (D). The fraction of bots, f_b reaching the target area (shown in fig. (1)), as a

*This work was not supported by any organization

[1]Akshatha Jagadish is with Indian Institute of Science, Bangalore akshathaj@iisc.ac.in
[2]Manoj Varma is with Indian Institute of Science, Bangalore mvarma@iisc.ac.in

function of time, is calculated by integrating the Gaussian density function as shown in (1).

$$f_b(t) = \int_{l_x-a}^{l_x+a} \frac{1}{\sqrt{4\pi D_x t}} e^{\left(\frac{-x^2}{4D_x t}\right)} dx \int_{l_y-a}^{l_y+a} \frac{1}{\sqrt{4\pi D_y t}} e^{\left(\frac{-y^2}{4D_y t}\right)} dy \quad (1)$$

where $l_x = l\cos(\theta)$ and $l_y = l\sin(\theta) \Rightarrow (l_x^2 + l_y^2 = l^2)$ and D_x and D_y are diffusion coefficients in the x and y directions respectively.

Eqn. (1), after simplification, reduces to (2)

$$f_b(t) = \frac{a^2}{\sqrt{\pi D_x t}\sqrt{\pi D_y t}} e^{-\left(\frac{l_x^2}{4D_x t} + \frac{l_y^2}{4D_y t}\right)} \quad (2)$$

For an isotropically diffusing swarm, $D_x = D_y = D$. Thus (2) reduces to (3).

$$f_{b,iso}(t) = \frac{a^2}{\pi D t} e^{-\left(\frac{l^2}{4Dt}\right)} \quad (3)$$

Since the target is absorbing in nature, the bots get absorbed before they can reach the centre of the target. Hence, it is enough to consider the bots reaching the boundary of the target. Let the boundary of the target be resolved into sub-targets (as shown in fig. (2)) of size a_{sub}, which is obtained by constraining the parameter $\frac{a_{sub}^2}{D}$ to be a decided maximum. The fraction of bots reaching the boundary of the absorbing target is denoted by f_b'. This is given by (4).

$$f_b'(t) = \sum_{i=1}^{m} \frac{a_{sub}^2}{\pi D t} e^{-\left(\frac{l_{sub}(m)^2}{4Dt}\right)} \quad (4)$$

where m = number of sub-target regions on the boundary. Note that l_{sub} changes for each new sub-target.

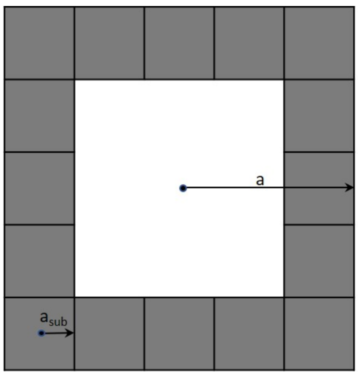

Fig. 2. Sub-target regions in the boundary of the target

The capture efficiency of the target is obtained by accumulating the bots that reach the target area at each time step and then normalizing that sum. This is calculated by accumulating the discretized fraction of bots, $f_b'(n)$, where $t = \Delta t n$. Let this be denoted as η given by (5).

$$\eta(n) = \begin{cases} f_b'(n) & : n = 1 \\ f_b'(n) + \left(1 - f_b'(n)\right)\eta(n-1) & : n > 1 \end{cases} \quad (5)$$

Fig. (3) shows the simulation results in comparison with the mathematical model described above. Note that there is a gap between the two plots and the mathematical model is thus approximately close to the simulation.

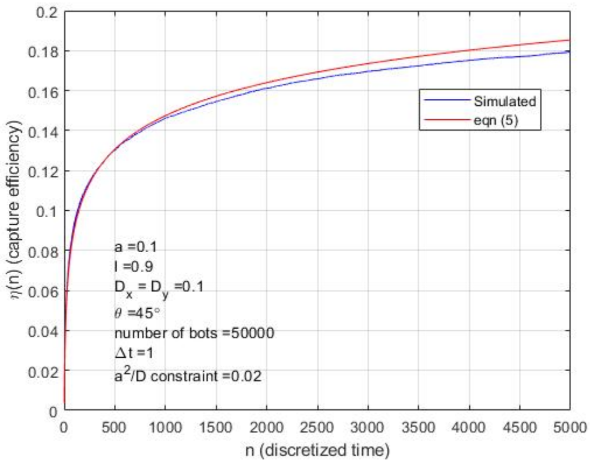

Fig. 3. Mathematical model and simulated capture efficiency

Other qualitative observations from the simulations are increase in capture efficiency η with increase in a, decrease in l and/or decrease in D.

IV. CONTROL APPLICATION

We look at two control techniques here to improve the capture efficiency that the swarm attains naturally. They are named as velocity control 1 and velocity control 2. In both the techniques, velocity is applied to the swarm in the direction of the target, which leads to the change in the mean of the swarm. In the first control technique, the velocity is applied indefinitely and in the second control technique, the application of velocity is stopped once the mean theoretically reaches the target. The simulation results of the same is represented in fig. (4).

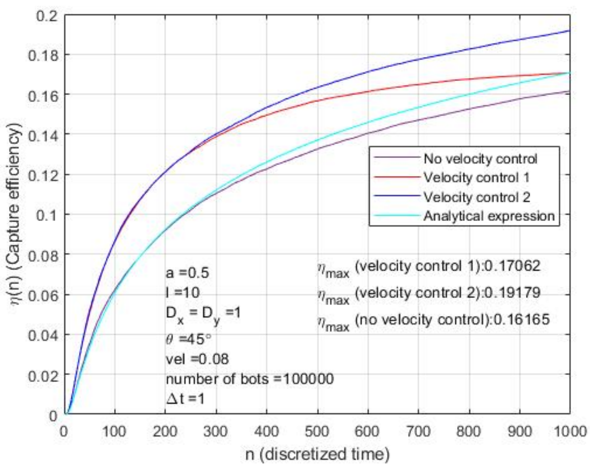

Fig. 4. Velocity or mean control simulation

We can observe here that velocity control 2 gives a better capture efficiency when compared to velocity control 1 over the natural capture efficiency (no velocity control). This is because the swarm, once the application of velocity stops, is left to diffuse very close to the target area in the second technique. In addition to this, we can also observe that the capture efficiency increases with increase the quantity of velocity applied. This is captured in fig. (5).

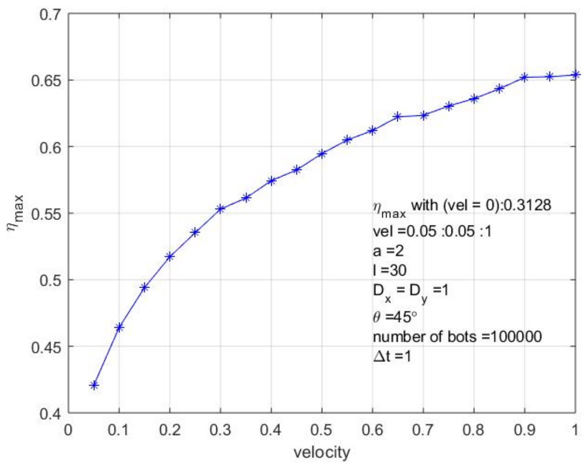

Fig. 5. Variation in capture efficiency with applied velocity in velocity control 2

V. CONCLUSIONS

The mathematical model that is used to describe the micro-robotic swarm is close to the simulated results and hence can be used to study the dependence of capture efficiency on various parameters of the system. The effect of diffusion coefficient, in particular, helps in designing the bots suitable for the targeted delivery application.

The velocity control 2 is better compared to velocity control 1 because of the proximity of swarm mean to the centre of the target. The capture efficiency improves with increase in velocity in the velocity control 2. These two points indicate that the study of optimal distance dependent velocity control and variance control to keep the swarm together would be a promising future research for fast and efficient targeted delivery of bots.

REFERENCES

[1] S. Shahrokhi, A. Mahadev, and A. T. Becker, "Algorithms for shaping a particle swarm with a shared input by exploiting non-slip wall contacts," in *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Sep. 2017, pp. 4304–4311.

[2] S. Shahrokhi, L. Lin, C. Ertel, M. Wan, and A. T. Becker, "Steering a swarm of particles using global inputs and swarm statistics," *IEEE Transactions on Robotics*, vol. 34, no. 1, pp. 207–219, Feb 2018.

[3] I. S. M. Khalil, K. Youakim, A. Sánchez, and S. Misra, "Magnetic-based motion control of sperm-shaped microrobots using weak oscillating magnetic fields," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sep. 2014, pp. 4686–4691.

[4] J. Li, O. E. Shklyaev, T. Li, W. Liu, H. Shum, I. Rozen, A. C. Balazs, and J. Wang, "Self-propelled nanomotors autonomously seek and repair cracks," *Nano Letters*, vol. 15, no. 10, pp. 7077–7085, 2015, pMID: 26383602. [Online]. Available: https://doi.org/10.1021/acs.nanolett.5b03140

[5] S. Chandrasekhar, "Brownian motion, dynamical friction, and stellar dynamics," *Rev. Mod. Phys.*, vol. 21, pp. 383–388, Jul 1949. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.21.383