Decentralized Control Scheme for Swarm Robots with Self-Sacrifice

Takeshi Kano[1], Munehiro Asally[2,3], and Akio Ishiguro[1]

[1]Research Institute of Electrical Communication, Tohoku University, Sendai, Miyagi, Japan 980-8577
[2]School of Life Sciences, [3]Warwick Integrative Synthetic Biology Centre, University of Warwick, Coventry, United Kingdom CV4 7AL
Correspondence: tkano@riec.tohoku.ac.jp

Abstract

Altruistic behaviors, such as self-sacrifices, are commonly observed in diverse living systems from bacteria to animal societies. Motivated by the fact that self-sacrifices of individuals can benefit the entire populations, we developed a decentralized control scheme with self-sacrifice by extending the *Slimebot* model. When an agent is not performing favorably, the agent self-sacrifices by stopping the motion and transferring its energy to nearby agents. We demonstrate via simulations that the proposed control scheme enables the agents to perform tasks effectively under several environments.

Collective behaviors can achieve non-trivial macroscopic functionalities including adaptability, scalability, and fault tolerance (Reynolds, 1987; Helbing and Molnár, 1995). For such functionality, self-sacrifices of individuals often play crucial roles for the benefit of entire population in natural and social systems, such as programmed cell death (Allocati et al., 2015) and altruistic behavior of social insects (Ratnieks and Wenseleers, 2007). Inspired by these biological self-sacrificing mechanisms, several swarm robotic systems incorporating self-sacrifices are beginning to be developed (Sugawara et al., 2017; Floreano et al., 2008).

In this study, we apply the concept of self-sacrifice in a new way within the swarm robotic field. Namely, we design a swarm robotic system for better efficiency of energy resources via self-sacrifices. It is designed by extending a model of a swarm robotic system inspired by the locomotion of true slime mold, the *Slimebot* (Ishiguro et al., 2006). We demonstrate by simulations that the proposed model allows the agents to effectively utilize their energy as a collective through self-sacrifices. Importantly, it also leads to better achievements of tasks under challenging conditions.

In our model, N agents exist on a two-dimensional plane, and their task is to move toward an attractant through their coordination. Schematic of agents is shown in Fig. 1. Each agent has radially arranged arms whose lengths are variable, and a friction control unit implemented at the bottom. The friction control unit alter the friction coefficient between the agent and the ground.

When an agent contacts with another agent, connection between the two is established; that is, they are connected

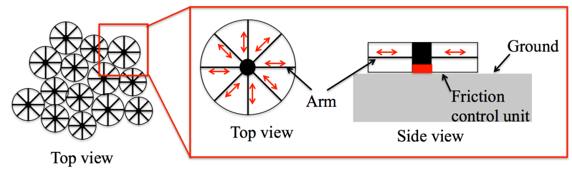

Figure 1: **Schematic of agents.**

by a parallel mechanism of a spring and a damper. When the force above the threshold f_{th} is applied to the connection, the connection is cut; that is, the parallel mechanism disappears.

A phase oscillator is implemented in each agent. The arm length of the ith agent, d_i, and the friction coefficient between the ith agent and ground, η_i, are determined by oscillator phase as

$$d_i = d_0 + a \sin \phi_i, \quad (1)$$
$$\eta_i = \mu_i \zeta_i, \quad (2)$$

where d_0 and a are positive constants, μ_i denotes the roughness of the ground, and $\zeta_i = \zeta_l$ for $0 \leq \phi_i < \pi$ and $\zeta_i = \zeta_h$ for $\pi \leq \phi_i < 2\pi$ with $\zeta_h > \zeta_l$.

Although an agent is unable to change its position by itself, it can move through the interaction with connected agents when there are phase shifts between them. For example, when the ith and jth agents are connected with their phases being $\pi \leq \phi_i < 2\pi$ and $0 \leq \phi_j < \pi$, respectively, the jth agent can move by pushing or pulling agent i which anchors to the ground. Considering this, the time evolution of ϕ_i is designed as

$$\dot{\phi}_i = \omega_i + \epsilon \sum_{j \in \text{connect}} \sin(\phi_j - \phi_i), \quad (3)$$

where $\sum_{j \in \text{connect}}$ denotes summation over the connected agents. Here, ϵ is a positive constant, and $\omega_i = \omega_h$ for the agents that receive attractant stimuli while $\omega_i = \omega_l$ for the others with $\omega_h > \omega_l$. The second term on the right-hand side of Eq. (3) works such that the connected agents synchronize with in-phase. Phase gradient generates owing to the inhomogeneity of ω_i, which enables the agents to move toward the attractant.

Each agent initially has the energy E_0. It is consumed by the work done by the actuators and the dissipation, and it is assumed that the energy can be transferred to the connected agents. The time evolution of the remaining energy of the ith agent E_i is designed as

$$\dot{E}_i = -W_i - D_i + e_i + \sigma \sum_{j \in \text{connect}} \left(\frac{E_j}{\omega_j n_j} - \frac{E_i}{\omega_i n_i} \right), \quad (4)$$

where W_i and D_i denote the work done by the actuator and the dissipation energy per unit time, respectively, e_i denotes the energy transferred from agents that self-sacrifice (see below), σ is a positive constant, and n_i denotes the number of agents connected to agent i. The fourth term on the right-hand side represents transportation of the energy between the connected agents. Owing to this term, the energy of agents with small ω_i and n_i (in most cases, agents that are located at the edge of a cluster but do not receive attractant stimuli) tends to become smaller than that of the others.

The basic concept of self-sacrifice is that the agents not performing well suicide themselves and transfer the remaining energy to the connected agents so that they can function longer. The performance of each agent can be evaluated by the mean velocity toward the attractant for the recent past. Thus, agent i self-sacrifices when the following condition is satisfied:

$$E_i \leq \lambda \max(V_0 - V_i, 0) E_0, \quad (5)$$

where λ and V_0 are positive constants, and V_i denotes the mean velocity toward the attractant for the recent past. When an agent self-sacrifices, its remaining energy is equally distributed to the connected agents, and then it stops active motion cutting all the connections with others.

Simulations were performed under the following two types of environments:

1) Agents traverse a slippery terrain of the friction coefficient μ (Fig. 2(a)).
2) Agents traverse an area in which they receive external force $-F_{\text{ext}}\mathbf{e}$ where $\mathbf{e}$ denotes the unit vector that points the attractant (Fig. 2(b)).

To investigate how the self-sacrifice works depending on the environment, the parameter λ as well as μ and F_{ext} was varied. The results were evaluated by the number of agents that reached the goal. The number of the agents N was 50 and the other parameters were determined by trial-and-error.

The results are shown in Fig. 3 (movies for can be downloaded from https://fsa.fir.riec.tohoku.ac.jp/fircloud/index .php/s/P6hUwPeDVBlsLgE). When λ was zero (*i.e.*, no self-sacrifice), each agent lived until the remaining energy becomes zero. In this case, all agents reached the goal under preferable environments (large μ or small F_{ext}). However, none of the agents reached the goal under the condition where μ is small or F_{ext} is large. As λ increased, several agents were able to reach the goal owing to self-sacrifice in wider range of conditions, although it decreased the performance slightly under preferable environments. These results demonstrate that the self-sacrifice system enables the collective to perform robustly in wide range of conditions through cooperative resource allocations.

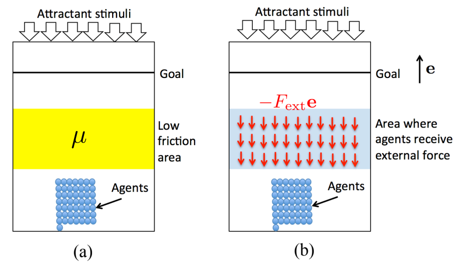

Figure 2: **Environments examined: (a) Environment 1) and (b) Environment 2).**

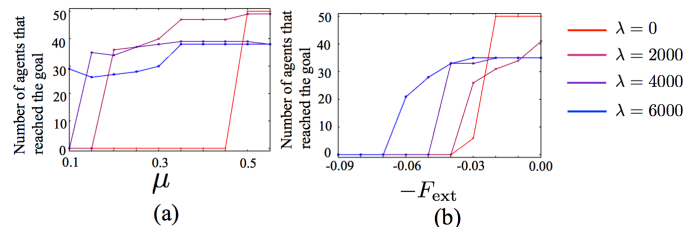

Figure 3: **Simulation results (a) when λ and μ are varied in Environment 1) and (b) when λ and F_{ext} are varied in Environment 2).**

In conclusion, we have proposed a decentralized control scheme for swarm robots that exploit self-sacrifice by extending the *slime-bot* model, and have validated it by simulations. Our results will pave the way for developing swarm robots that can perform tasks under challenging environments, *e.g.*, disaster areas. Investigating the applicability of the proposed scheme under unstructured real environments where noise is non-negligible remains as a future work.

Acknowledgements

The authors would like to thank Prof. Ken Sugawara at Tohoku-Gakuin University and Wataru Suda at Tohoku University for their helpful suggestions.

References

Allocati, N., Masulli, M., Di Ilio, C., and De Laurenzi, V. (2015). Die for the community: an overview of programmed cell death in bacteria. *Cell Death & Disease*, 6(e1609).

Floreano, D., Mitri, S., Perez-Uribe, A., and Keller, L. (2008). Evolution of atruistic robots. In *Lecture Notes in Computer Science (LNCS), Proceedings of the WCCI 2008*, volume 5050, pages 232–248. Springer Berlin/Heidelberg.

Helbing, D. and Molnár, P. (1995). Social force model for pedestrian dynamics. *Physical Review E*, 51:4282–4286.

Ishiguro, A., Shimizu, M., and Kawakatsu, T. (2006). A modular robot that exhibits amoebic locomotion. *Robotics and Autonomous Systems*, 54:641–650.

Ratnieks, F. and Wenseleers, T. (2007). Atruism in insect societies and beyond: voluntary or enforced? *TRENDS in Ecology and Evolution*, 23:45–52.

Reynolds, C. (1987). Flocks, herds, and schools: a distributed behavioral model. *Computer Graphics*, 21:25–34.

Sugawara, K., Shishido, M., and Doi, Y. (2017). Casualty-based cooperation in swarm robots. In *SWARM 2017: The 2nd International Symposium on Swarm Behavior and Bio-Inspired Robotics*, pages 61–62.