Non-trivial behaviors emerging from a simple decentralized rules (Part 2): A case study with swarming of individuals

Takeshi Kano[a], Naoki Matsui[a], Eiichi Naito[b], Takenobu Aoshima[b], Akio Ishiguro[a]
[a]Research Institute of Electrical Communication, Tohoku University, Japan
{*tkano, ishiguro*}@*riec.tohoku.ac.jp*, *naoki.matsui.31@gmail.com*
[b]Business Innovation Division, Panasonic Corporation, Japan
{*naito.eiichi, aoshima.takenobu*}@*jp.panasonic.com*

1 Introduction

In many research fields including the field of adaptive motion of animals, mathematical models and robots have been developed to understand essential mechanisms underlying certain phenomena or to achieve certain tasks. Our approach in this study is different: we propose mathematical models and robots that generate non-trivial behaviors just for curiosity, after which we discuss their applications.

Here we focus on swarming of individuals. We have recently proposed a simple mathematical model of swarm formation [1, 2]. This model was inspired by the friendship formation process in human society (for example, a process in which several cliques are formed spontaneously in certain communities such as classes in schools). It was demonstrated via simulations of the proposed model that various patterns emerge by changing the parameters. Some of the patterns are dynamic and lifelike, and it was found that nonreciprocal property of the interaction between agents plays a crucial role for the emergence of these patterns.

Although this model was developed without any motivation, it has many possible applications that range from science to engineering, such as understanding the core principle of self-organization [1], elucidating the essential mechanism of the behavior of active matters [3], and designing swarm robots that can effectively perform tasks [4]. In this study, we move one step forward into the engineering applications. Specifically, swarm robots that implement the proposed model are developed. We demonstrate that the developed robots can roughly reproduce the simulation results.

2 Model

Let us briefly summarize the model which we proposed previously [1, 2]. Particles, each of which represents a person in a community, exist on a two-dimensional plane, and the position of the ith particle ($i = 1, 2, \cdots, N$) is denoted by $\mathbf{r}_i$. The time evolution of $\mathbf{r}_i$ is given by

$$\dot{\mathbf{r}}_i = \sum_{j \neq i} (k_{ij}|\mathbf{R}_{ij}|^{-1} - |\mathbf{R}_{ij}|^{-2})\hat{\mathbf{R}}_{ij}, \qquad (1)$$

where $\mathbf{R}_{ij} = \mathbf{r}_j - \mathbf{r}_i$, $\hat{\mathbf{R}}_{ij} = \mathbf{R}_{ij}/|\mathbf{R}_{ij}|$, and k_{ij} denotes a constant that represents "to what extent person i prefers person j." When $k_{ij} = k_{ji}$, the interaction between the ith and jth particles is described by a potential, and the distance between the ith and jth particles tends to converge to k_{ij}^{-1} (if $k_{ij} > 0$). However, because k_{ij} is not necessarily equal to k_{ji}, *i.e.*, the interaction can be non-reciprocal, Eq. (1) is generally a non-equilibrium open system in which both energy and momentum are non-conservative.

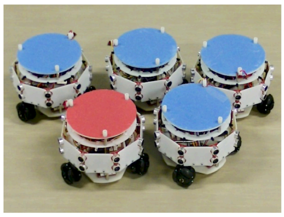

Figure 1: Overview of the robots.

Simulation results for several k_{ij} values can be downloaded from
http://www.riec.tohoku.ac.jp/∼tkano/ECAL_Movie1.mp4.
It is found that various nontrivial patterns emerge.

3 Robot

Because detecting the k_{ij} values for arbitral parameter sets is technically difficult, in this study, we developed robots applicable only to the case where $N = 5$ and $k_{ij} = k_p + k_m$ $(i = 1, 2 \leq j \leq 5)$, $k_p - k_m$ $(2 \leq i \leq 5, j = 1)$ and k_a $(2 \leq i \leq 5, 2 \leq j \leq 5)$, where k_p, k_m, and k_a are constants. This case was studied previously by simulations and mathematical analyses, and it is already known that versatile patterns, *e.g.*, static configuration, translational motion with relative position among particles fixed, and limit cycle oscillation, emerge by changing the parameter values [2].

Figure 1 shows the overview of the robots. Each robot is cylindrical shape, and its diameter and mass are 0.19 m and 1.2 kg, respectively. Three omni-wheels (TYPE 2571, Tosa densi Co.,Ltd., slightly modified) are attached equidistantly at the bottom (Fig. 2(a)). Each omni-wheel consists of a couple of discs (Fig. 2(b)), and they rotate owing to the torque generated by a DC motor (Maxon Japan Corporation, RE-max17 GB 4.5W SL 2WE) (Fig. 2(a)). The motor axes are in parallel to the radial direction of the robot. Three barrels are implemented equidistantly in each disc so that the wheel can passively move in the direction parallel to the motor axis (Fig. 2(b)). Thus, the robot can move omni-

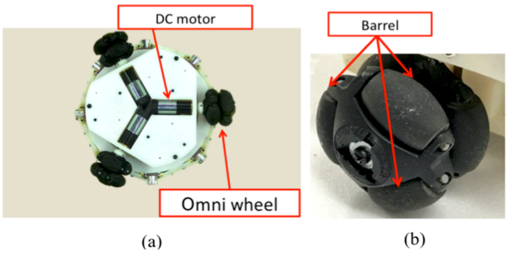

Figure 2: Detailed structure of the robot: (a) bottom view and (b) magnified view of an omni-wheel.

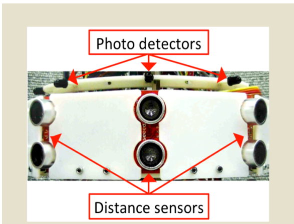

Figure 3: Distance sensors and photodetectors.

directionally by changing the output ratio of the motors.

Eight pairs of ultrasonic distance sensor modules (101990004, Speed Studio Co.) and photodetector (SID1K10CM, Linkman Co.) are attached equidistantly on the side surface of the robot (Fig. 3). Each distance sensor can detect robots within 1.7 m and $\pm\pi/12$ rad from the direction it points. The sensor value was updated every 0.1 second. Thus, the outputs of the distance sensors enable the robot to identify the relative position of its neighboring robots with respect to itself in most cases. Infrared light LED is attached to one of the robots ($i = 1$). The robots can identify the k_{ij} values of the neighboring robots by detecting the infrared light via the photodetectors (*i.e.*, $j = 1$ if the ith robot detects the infrared from the jth robot, otherwise $2 \leq j \leq 5$).

A microcomputer (mbed:NXP LPC 1768) is embedded in each robot to determine its direction of motion and velocity on the basis of the sensory information obtained. The values of k_p, k_m, and k_a can be changed via wireless communication (Programmable XBee ZB(S2C)/Wire antenae type, Digi Co.)

4 Experimental results

We implemented the proposed model (Eq. (1)) in the robots developed. The color of the robot was red for $i = 1$ and blue for $2 \leq i \leq 5$ (Fig. 1). Figure 4 shows the results when $k_p = 2.0$, $k_m = -1.0$, $k_a = 2.0$. The red robot was initially surrounded by the blue robots. The robots exhibited translational motion whereby the red robot was chased by the blue robots (Fig. 4(a)). This behavior qualitatively agrees with the simulation result (Fig. 4(b)).

Next, we performed experiments with $k_p = 1.6$, $k_m = 2.4$, $k_a = 1.6$. The red robot was initially surrounded by the blue robots. The red robot moved periodically with surrounded by the blue robots (Fig. 5(a)). This behavior is similar to the simulation result (Fig. 5(b)). However, the behavior of the robots is not completely periodic but somewhat

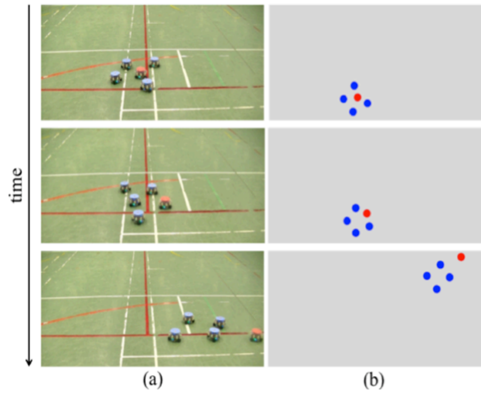

Figure 4: Result for $k_p = 2.0$, $k_m = -1.0$, and $k_a = 2.0$: (a) Robot experiment and (b) Simulation.

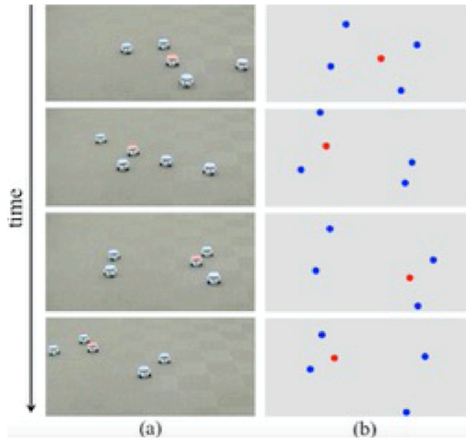

Figure 5: Result for $k_p = 1.6$, $k_m = 2.4$, and $k_a = 1.6$: (a) Robot experiment and (b) Simulation.

irregular, compared with the simulation result.

The discrepancy between the robot experiment and the simulation are considered to be due to the limitation of the function of the sensors implemented in the robots. For example, the sensor range is limited, and the time interval for the update of the sensor value is not short enough. Further, noise in the sensor output cannot be neglected. These problems still need to be solved.

Acknowledgments

This work was supported by Japan Science and Technology Agency, CREST.

References

[1] T. Kano, K. Osuka, T. Kawakatsu, N. Matsui, and A. Ishiguro, A minimal model of collective behaviour based on non-reciprocal interactions, *Proc. 14th Euro. Conf. Artif. Life*, pp. 237-244, 2017.

[2] T. Kano, K. Osuka, T. Kawakatsu, A. Ishiguro, Mathematical analysis for non-reciprocal-interaction-based model of collective behavior, *J. Phys. Soc. Japan*, Vol. 86, 124004, 2017.

[3] S. Tanaka, S. Nakata, and T. Kano, Dynamic ordering in a swarm of floating droplets driven by solutal Marangoni effect, *J. Phys. Soc. Japan*, Vol. 86, 101004, 2017.

[4] T. Kano, E. Naito, T. Aoshima, and A. Ishiguro, A simple decentralized control scheme for swarm robots that can perform spatially distributed tasks in parallel, *Proc. 2nd Int. Symp. Swarm Behav. Bio-Inspi. Rob. (SWARM)*, pp. 260-261, 2017.