sists of 80 agents and directions of transitions of agents are not analogous. A swarm ball continuously contains internal turbulence. Initial configurations of agents in these gates are randomly given in a designated area in the input position, where no external noise is coupled with the transition rule for the agent. The performance of these gates is 100 percent for OR, AND, and NOT gates. Because we can implement OR, AND, and NOT gates, we can calculate any propositional logic sentence.

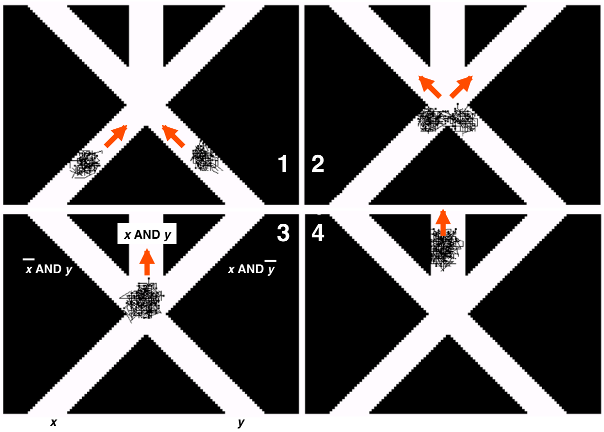

Figure 3. A series of snapshots (1, 2, 3, and 4) in an AND gate of swarm balls. Swarm balls located at the x and y positions consist of 40 agents. Each agent is represented by a square with its 5-step trajectory. Red arrows represent the direction a swarm ball is moving toward.

Finally, we discuss the robustness of the gates. As mentioned before, the OR gate acts very well against external perturbation. Here, we estimate the performance of the AND gate under a high rate of external noise. In the simulation, the external noise that is coupled with the operation of velocity matching is defined as a random value ξ selected with equal probability from $[-\lambda, \lambda]$. When the velocity of each agent in a two-dimensional space v is projected in the x and y planes denoted by v_x and v_y, the external noise is coupled by $v_x + \xi$ and $v_y + \xi$ and then normalized to make the length of the velocity be 1. We estimate performance within the range $0.0 \leq \lambda \leq 0.2$ when comparing our model of $P = 20$ with one with $P = 1$. If $P = 20$, multiple potential transitions play a role in mutual anticipation that can contribute to collective behavior. If $P = 1$, coherence of swarm results only from velocity matching.

Figure 4 shows performance of an AND gate implemented by our swarm model under a perturbed condition. The performance is defined by the success rate of the gate. In each experiment, we set 40

https://doi.org/10.25088/ComplexSystems.20.2.93

agents in the input positions x and y. If 80% of the agents (64 agents) in a united swarm reach the output exit of x AND y, we determine the result for the experiment to be a success; otherwise, it is a failure. The performance is defined by the number of successful experiments divided by the total number of experiments (100 experiments). Since the swarm model with $P = 1$ corresponds to the well-known boids model, the external perturbation directly influences the collective behavior of swarms. Therefore, as the strength of perturbation increases, the performance rapidly decreases.

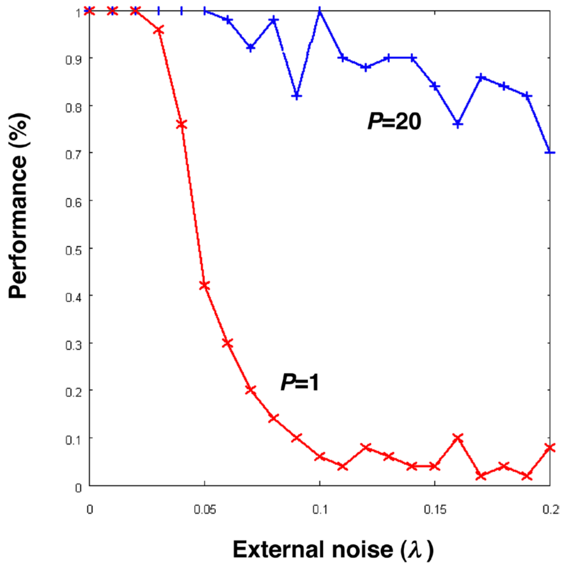

Figure 4. Performance of an AND gate implemented by the swarm model. Performance is plotted against the strength of external perturbation. A swarm model with $P = 20$ is compared to one with $P = 1$. The model with $P = 1$ can correspond to boids.

In contrast, the performance of our swarm model with $P = 20$ does not decrease drastically as the strength of perturbation increases. A large possibility of transitions can increase the probability of the presence of highly popular sites, which increases the possibility of mutual anticipation that results in the collective behavior of swarming. External perturbation also increases the possibilities of transitions. In this sense the external perturbation cannot be distinguished from potential transitions, and can produce the same contribution as increasing the number of potential transitions. The external perturbation plays a role in generating and keeping a swarm ball. The directed motion of a swarm along the wall, however, depends on the strength of velocity matching. That is the reason why the performance of the AND gate implemented by swarms with $P = 20$ is slightly decreased.

Note that the cohesive power does not weaken despite low performance.

3.2 Experimental Gate Implemented by Real Soldier Crabs

We first implemented the logical gate of swarm collision by real soldier crabs, *Mictyris guinotae*. The corridor is made of acrylic plastic plates, and the gradient to move was implemented by using an orange-colored intimidation plate. The reason for having an intimidation plate is because birds are the main natural predators feeding on soldier crabs and there are usually no shadows in the lagoon except for bird shadows. This is why the crabs are very sensitive to the shadows made by standing and moving objects. Thus, the intimidation plate can trigger soldier crabs to move away from the shadowed region. The floor of the experimental gate is made of cork to provide a comfortable footing for the crabs.

Figure 5(a) shows the AND gate of swarm collision. First, we close the gate and set a swarm of solider crabs for either or both input spaces surrounded by walls and a gate. The crabs are left for about two minutes to relax. After the crabs relax, the folded intimidation plate is extended and placed vertically; then crabs start moving along the corridor. Real-world crabs indeed behave similarly to simulated crabs. If the input for (x, y) is $(1, 0)$ or $(0, 1)$, a swarm representing the value of 1 is set by 40 crabs. If the input for (x, y) is $(1, 1)$, each swarm representing a value of 1 is set by 20 crabs.

Figure 5(b) to (e) shows the two results of the AND gate experiment for a particular swarm consisting of 40 individuals. First, 40 individuals are divided into two parts of 20 individuals each, and set for input space $(x, y) = (1, 1)$. In other cases where $(x, y) = (1, 0)$ or $(0, 1)$, 40 individuals are set for input space A or B, respectively. In any input case, both intimidation plates are unfolded and stood vertically soon after the gate is opened. The bars of Figure 5(b) to (e) show the rate (%) of individuals reaching output 1, 2, or 3. Red or blue bars represent the result of the first and second experiments for the same population of individuals. Two experiments have the same tendency, such that for the input $(1, 0)$ and $(0, 1)$, most of a swarm goes straight (i.e., A to 3 or B to 1 in Figure 5(b) to (d)), and for the input $(1, 1)$ individuals derived from input spaces A and B are united and go to the central part of the output, called 2. These results are approximated by our model simulation.

Figure 5(e) shows experimental results for 21 trials, where each trial was conducted for 40 individuals. Each bar represents the rate over all trials. The frequency histogram shows that for inputs $(1, 0)$ and $(0, 1)$, individuals of a swarm go straight or to the central corridor, meaning that most of a swarm goes straight to some extent. It also shows that for input $(1, 1)$, most of a swarm goes to the central corridor after the swarms collide. If the output of either 0 or 1 is determined by the difference in the number of individuals reaching outputs

https://doi.org/10.25088/ComplexSystems.20.2.93

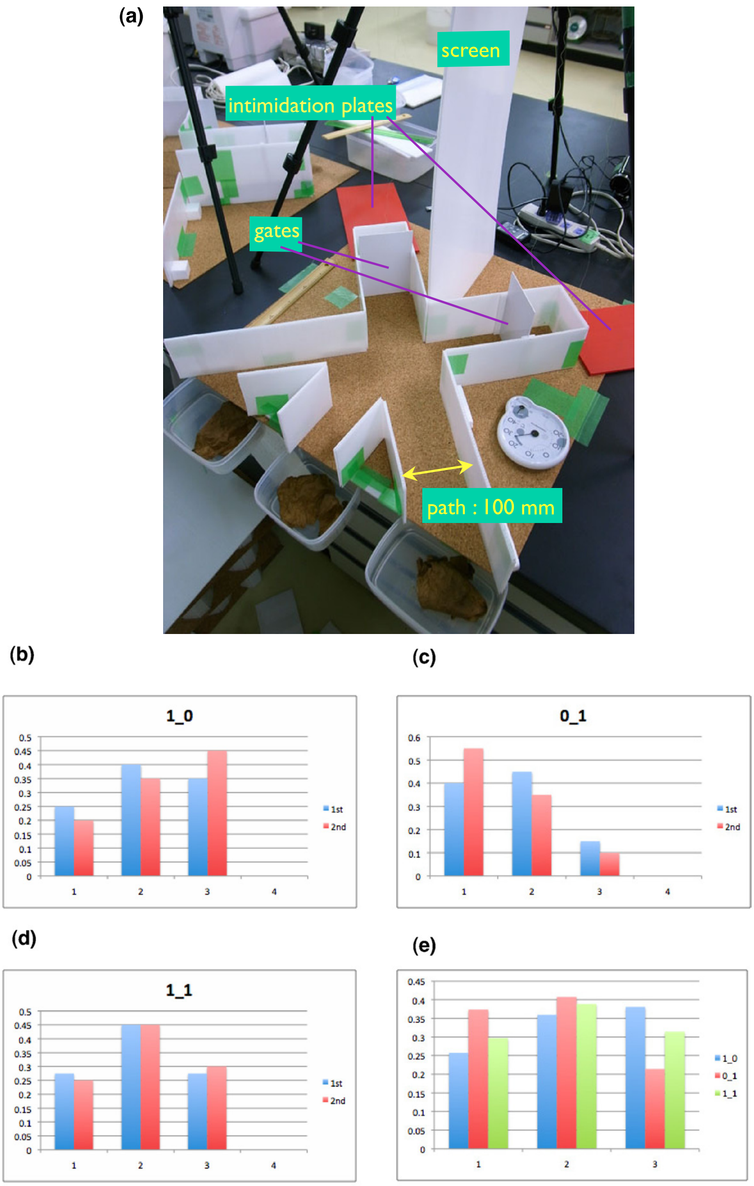

Figure 5. (a) Implementation of an AND gate for real soldier crabs. Input space for input x or y is located at the space behind the intimidation plate. The symbols 1, 2, and 3 represent output for NOT(x) AND y, x AND y, and x AND NOT(y), respectively. (b)–(e) The experimental results of AND gate implemented by real soldier crabs. (b) Frequency distribution of output 1, 2, and 3 for the input (1, 0). Output 4 represents the rate of individuals that do not reach the output in a limited time. (c) Frequency distribution for the input (0, 1). (d) Frequency distribution for the input (1, 1). (e) Frequency distribution of outputs 1, 2, and 3 over 21 trials.

https://doi.org/10.25088/ComplexSystems.20.2.93

1 and 3, the output is 0 if the difference exceeds 10% of all individuals (i.e., four individuals); it is 1 otherwise. If the determinant is applied to 21 trials of the AND gate experiment, performance of the AND gate for inputs (1, 0), (0, 1), or (1, 1) is 0.81, 0.76, or 0.52, respectively.

Although the experiment implemented by real soldier crabs is just a preliminary work, the performance of the AND gate is not bad. Since the OR gate can be easier to implement, the swarm collision computation can be naturally constructed. The gradient of the corridor is tested by other devices such as illumination, physical gravitational stimulus produced by slope, and some combinations. The condition of a swarm in the experiment in a room is different from that in a natural lagoon. If good enough conditions are provided for the experiment in a room, robustness of a swarm can be reconstructed.

4. Conclusion

Soldier crabs that live in tropical lagoons wander as a huge swarm in the low tidal period and live under the sand in the high tidal period. Each individual sometimes wanders freely, and is aggregated into a huge swarm triggered by a natural enemy or tidal movement dependent on the lagoon topography. Once a swarm is generated, individuals in the peripheral regions dynamically exchange their places and the internal turbulence of the crab becomes responsible for the same swarm motion. Therefore, even if the boundary of a swarm is definitely sharp and smooth, the internal structure of the swarm is dynamical and random. The mutual anticipation can negotiate perturbation and the force to make an order. In this paper, we implement ballistic computing [15] by using such a robust swarm. In the natural implementation of ballistic computation, it is difficult to refer to robustness of computation. For example, ballistic computation implemented by Belousov–Zhabotinsky (BZ) reactions is unstable without well-controlled conditions [16]. Our model suggests that biological computation is more robust even under perturbed environments.

Ethical Note

No specific license was required for this work. The duration of any single experiment was so short that no crab was ever endangered. The crabs were kept in comfortable conditions and after all experiments were released to their natural habitat. Furthermore, on visual inspection, no crabs appeared to have been injured or adversely affected by the experiments.

https://doi.org/10.25088/ComplexSystems.20.2.93

References

[1] A. Adamatzky and B. De Lacy Costello, “Binary Collisions between Wave-Fragments in a Sub-Excitable Belousov–Zhabotinsky Medium,” *Chaos, Solitons & Fractals*, **34**(2), 2007 pp. 307–315. doi:10.1016/j.chaos.2006.03.095.

[2] A. Adamatzky. “Slime Mould Logical Gates: Exploring Ballistic Approach.” (May 13, 2010) arXiv:1005.2301v1.

[3] A. Adamatzky, B. De Lacy Costello, and T. Asai, *Reaction-Diffusion Computers*, Boston: Elsevier, 2005.

[4] K. Yoshikawa, I. M. Motoike, T. Ichino, T. Yamaguchi, Y. Igarashi, J. Gorecki, and J. N. Gorecka, “Basic Information Processing Operations with Pulses of Excitation in a Reaction-Diffusion System,” *International Journal of Unconventional Computing*, **5**(1), 2009 pp. 3–37.

[5] A. Toth, V. Gaspar, and K. Showalter, “Signal Transmission in Chemical Systems: Propagation of Chemical Waves through Capillary Tubes,” *Journal of Physical Chemistry B*, **98**(2), 1994 pp. 522–531. doi:10.1021/j100053a029.

[6] A. Toth and K. Showalter, “Logical Gates in Excitable Media,” *Journal of Chemical Physics*, **103**(6), 1995 p. 2058. doi:10.1063/1.469732.

[7] T. Nakagaki, H. Yamada, and A. Toth, “Intelligence: Maze-Solving by an Amoeboid Organism,” *Nature*, **407**, 2000 p. 470. doi:10.1038/35035159.

[8] A. Adamatzky, *Physarum Machines: Building Computers from Slime Mould*, Singapore: World Scientific, 2010.

[9] N. Margolus, “Physics-Like Models of Computation,” *Physica D*, **10**(1–2), 1984 pp. 81–95. doi:10.1016/0167-2789(84)90252-5.

[10] S. Tsuda, M. Aono, and Y.-P. Gunji, “Robust and Emergent Physarum Logical-Computing,” *Biosystems*, **73**(1), 2004 pp. 45–55.

[11] R. Rosen, *Anticipatory Systems: Philosophical, Mathematical, and Methodological Foundations*, New York: Pergamon Press, 1985.

[12] Y.-P. Gunji, H. Murakami, T. Niizato, A. Adamatzky, Y. Nishiyama, K. Enomoto, M. Toda, T. Moriyama, T. Matsui, and K. Iizuka, “Embodied Swarming Based on Back Propagation through Time Shows Water-Crossing, Hourglass and Logic-Gate Behaviors,” in *Proceedings of the Eleventh European Conference on the Synthesis and Simulation of Living Systems (ECAL 2011)*, Paris, France (T. Lenaerts, M. Giacobini, H. Bersini, P. Bourgine, M. Dorigo, and R. Doursat, eds.), Cambridge, MA: The MIT Press, 2011 pp. 294–301.

[13] C. W. Reynolds, “Flocks, Herds, and Schools: A Distributed Behavioral Model,” *ACM SIGGRAPH Computer Graphics*, **21**(4), 1987 pp. 25–34. doi:10.1145/37402.37406.

[14] Y. Vicsek, A. Czirók, E. Ben-Jacob, I. Cohen, and E. Shochet, “Novel Type of Phase Transition in a System of Self-Driven Particles,” *Physical Review Letters*, **75**(6), 1995 pp. 1226–1229. doi:10.1103/PhysRevLett.75.1226.

https://doi.org/10.25088/ComplexSystems.20.2.93

[15] A. Adamatzky, *Collision-Based Computing*, London: Springer, 2002.

[16] B. De Lacy Costello, A. Adamatzky, I. Jahan, and L. Zhang, “Towards Constructing One-Bit Binary Adder in Excitable Chemical Medium,” *Chemical Physics*, **381**(1–3), 2011 pp. 88–89. doi:10.1016/j.chemphys.2011.01.014.

https://doi.org/10.25088/ComplexSystems.20.2.93