Scalable and Stable Patterns Generated by Heterogeneous Boid

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Heterogeneous boid

Boid is a simple model of animal group movements, with many agents communicating locally. Boid agents align and cohere with their neighbors, and avoid collisions with their nearest neighbors. Various patterns can be formed by varying the interaction between them. Boid originates from a fish school model (Sakai and Suzuki, 1972, 1973) and has since been widely applied (Reynolds, 1987; Olfati-Saber, 2006; Sayama, 2007; Vicsek and Zafeiris, 2012). Boid agents in the same cluster interact with each other (directly or indirectly through others), whereas agents in distant clusters cannot interact. To widen interactions, the agents should be unified into a single cluster. When the model remains (or repeats) in a certain pattern maintaining a unified cluster, this pattern is defined as *stable*.

A *heterogeneous boid* consists of many agents of a few types (Nakamura, 2020, 2022). Agents detect the types of neighbors and count them. The ith agent follows the motion equations ($1 \le i \le N$, where N is the *number of agents*).

$$\frac{\vec{x}_i(t+\Delta t) - \vec{x}_i(t)}{\Delta t} = \vec{v}_i(t) \quad (1)$$

$$\frac{\vec{v}_i(t+\Delta t) - \vec{v}_i(t)}{\Delta t} = \sum_{\{j:\left|\vec{\xi}_{i,j}(t)\right| < r_s(T_i,T_j)\}} \frac{w_s(T_i,T_j)\vec{\xi}_{i,j}(t)}{\left|\vec{\xi}_{i,j}(t)\right|} + \sum_{\{j:\left|\vec{\xi}_{i,j}(t)\right| < r_a(T_i,T_j)\}} \frac{w_a(T_i,T_j)\left(\vec{v}_j(t) - \vec{v}_i(t)\right)}{N_{a,i}} + \sum_{\{j:\left|\vec{\xi}_{i,j}(t)\right| < r_c(T_i,T_j)\}} \frac{w_c(T_i,T_j)\left(-\vec{\xi}_{i,j}(t)\right)}{N_{c,i}} \quad (2)$$

$\{j : \left|\vec{\xi}_{i,j}(t)\right| < r\}$ means *for all jth agents within r from ith agent, not including ith agent*. The terms in Eq. 2 represent *separation* (s), *alignment* (a), and *cohesion* (c), respectively.

- $\vec{x}_i(t)$ and $\vec{v}_i(t)$ denote the *position* and *velocity* of the ith agent at time t, respectively. The time lag from sensing to action Δt is one step. $\vec{\xi}_{i,j}(t) = \vec{x}_i(t) - \vec{x}_j(t)$ denotes the *distance* between ith and jth agents ($1 \le i,\ j \le N$). T_i and T_j denote the *types* of ith and jth agents ($1 \le T_i,\ T_j \le k \ll N$, where k is the *number of types*).
- $N_{a,i} = \sum_{\{j:\left|\vec{\xi}_{i,j}(t)\right| < r_a(T_i,T_j)\}} 1$, and $N_{c,i} = \sum_{\{j:\left|\vec{\xi}_{i,j}(t)\right| < r_c(T_i,T_j)\}} 1$. When $N_{a,i}$ or $N_{c,i} = 0$, the 2nd or 3rd term in Eq. 2 is 0.

The interaction of agents depends on the combination of their types. $r_s(g,h)$, $r_a(g,h)$, and $r_c(g,h)$ denote the *effective ranges* of the separation, alignment, and cohesion of the gth type agent affected by the hth type one ($1 \le g,h \le k$), and $w_s(g,h)$, $w_a(g,h)$, and $w_c(g,h)$ denote the *weights* of them. For simplicity, they are arranged in ($k \times k$) matrices as W_s=$[w_s(g,h)]$, $\ldots$.The set $\{W_s,\ W_a,\ W_c,\ R_s,\ R_a,\ R_c\}$ decides the local interaction of the agents.

This model was simulated under the following conditions.

- The agents travel inside a cube of (100×100×100). An agent nearing the boundary avoids it and bounces back into the cube. As the agent cluster turns at the boundary, the normal component of the 2nd term of Eq. 2 acts to slow the cluster. These keep the cluster at low speed.
- Simulations begin from the initial state, with the agents equally divided into types, distributed within a sphere around the cube center.

By adjusting the interaction, the model forms stable patterns with symmetrical structures (cluster form, agent flows, etc.), maintaining a unified cluster. Large-scale structures of them reflect the local interactions. Therefore, these patterns remain stable regardless of N, and are defined as *scalable*.

Static stable patterns formed by this model

In Nakamura (2020), the heterogeneous boid is simulated with fixed $W_s = \begin{bmatrix} 0.05 & 0.05 \\ 0.05 & 0.05 \end{bmatrix}$, $R_s = \begin{bmatrix} 1.0 & 1.0 \\ 1.0 & 1.0 \end{bmatrix}$, $R_a = \begin{bmatrix} 2.5 & 2.5 \\ 2.5 & 2.5 \end{bmatrix}$, and $R_c = \begin{bmatrix} 3.0 & 3.0 \\ 3.0 & 3.0 \end{bmatrix}$ and varying W_a and W_c. It forms the following three static stable patterns (Fig. 1a-c).

- *Hemispherical pattern:* when agents of the same type align and cohere more strongly than the others, the interface between them is minimized to a planar shape.

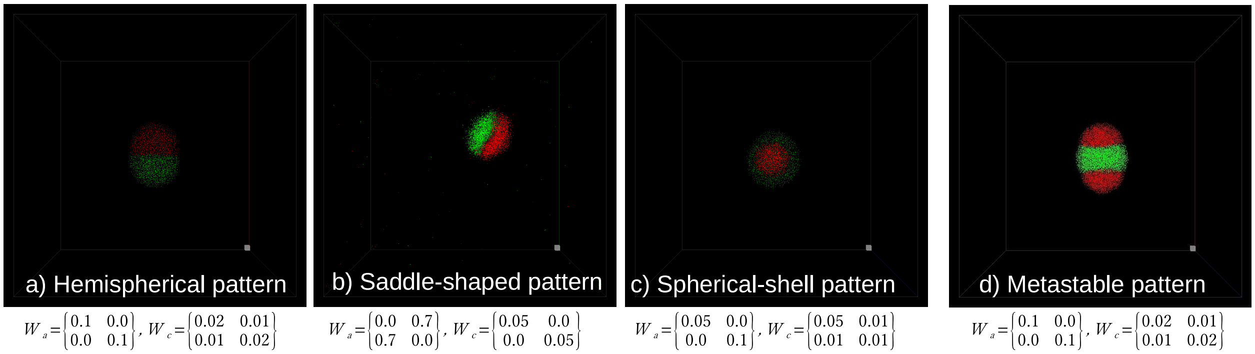

Figure 1: Three static stable patterns, and example of metastable pattern, 10,000 agents.

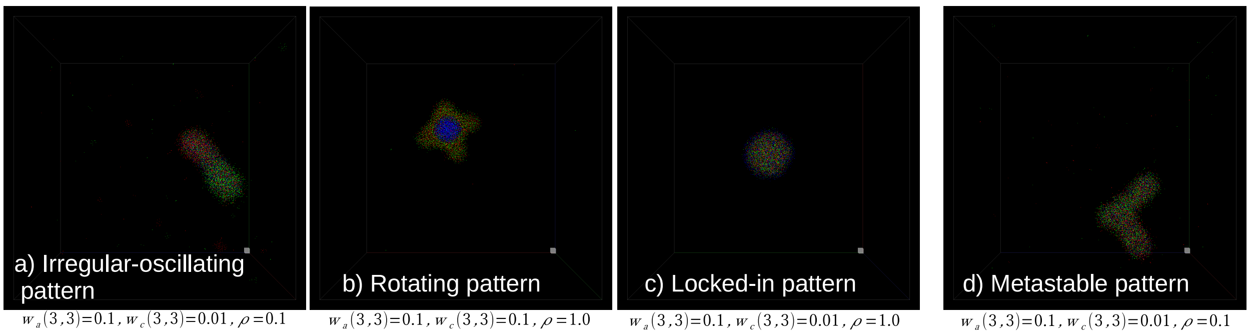

Figure 2: Three dynamic stable patterns, and example of metastable pattern, 10,000 agents.

- *Saddle-shaped pattern:* when agents cohere with the same type and are aligned with the other type, the interface is maximized to a saddle shape with low curvature.
- *Spherical-shell pattern:* when the interaction differs between types, the interface is minimized spherically.

These patterns are scalable. However, as N increases, the model increasingly forms metastable patterns, where stable patterns are fused (Fig. 1d). The symmetric stable pattern (Fig. 1a) is recovered from the metastable one, by adding proper noise or type transition to the agents' behavior.

Dynamic stable patterns formed by this model

In Nakamura (2022), the heterogeneous boid is simulated with the following conditions.

1. The two types of agents i) align with agents of the same type at a distance, and ii) move in reverse each other, passing through the gap between agents of the other type.
2. This causes the two types of agents to oscillate, breaking up the agent cluster. To unify the cluster, a third type of agent is introduced, as a stabilizer.

The interaction is expanded as $W_s = \begin{bmatrix}0.05 & 0.05 & 0.05\\ 0.05 & 0.05 & 0.05\\ 0.05 & 0.05 & 0.05\end{bmatrix}$, $W_a = \begin{bmatrix}0.03 & -0.006 & 0.0\\ -0.006 & 0.03 & 0.0\\ 0.0 & 0.0 & w_a(3,3)\end{bmatrix}$, $W_c = \begin{bmatrix}0.02 & 0.03 & 0.03\\ 0.03 & 0.02 & 0.03\\ 0.03 & 0.03 & w_c(3,3)\end{bmatrix}$, $R_s = \begin{bmatrix}1.0 & 0.1 & \rho\\ 0.1 & 1.0 & \rho\\ \rho & \rho & 1.0\end{bmatrix}$, $R_a = \begin{bmatrix}2.5 & 2.5 & 2.5\\ 2.5 & 2.5 & 2.5\\ 2.5 & 2.5 & 2.5\end{bmatrix}$, $R_c = \begin{bmatrix}3.0 & 3.0 & 3.0\\ 3.0 & 3.0 & 3.0\\ 3.0 & 3.0 & 3.0\end{bmatrix}$. By varying $w_a(3,3)$, $w_c(3,3)$, and ρ, three dynamic stable patterns (Fig. 2a-c, blue indicates the third type) are formed.

- The *irregular-oscillating pattern* repeats i) the reverse-phase oscillation of the two types of agents within the cluster (Fig. 2a), and ii) the temporary violent deformations of the cluster, intermittently.
- The *rotating pattern* shows the reverse rotation of the two types of agents around the core of agents of the third type, repeatedly deforming the cluster among i) spherical, ii) discoidal, and iii) branched phases (Fig. 2b).
- The *locked-in pattern* shows no rotation or oscillation, because the agents of the third type spread widely in the cluster, blocking agent flow (Fig. 2c).

These patterns are scalable. As N increases, the model increasingly forms long-lasting metastable patterns (Fig. 2d), which finally settles into stable pattern (Fig. 2a).

Conclusion

By adjusting interactions, the heterogeneous boid forms stable scalable patterns with the symmetric structures. As N increases, it increasingly forms metastable patterns, which can be avoided by improving agent behavior.

References

Nakamura, M. (2020). Two extensions of heterogeneous boid model to avoid metastable patterns. *Artificial Life and Robotics*, 25(4):578–587.

Nakamura, M. (2022). Dynamic patterns formed by heterogeneous boid model composed of agent groups moving reversely. *Artificial Life and Robotics*, 27(2):373–383.

Olfati-Saber, R. (2006). Flocking for multi-agent dynamics systems: algorithms and theory. *IEEE Transaction of Automatic Control*, 51(3):401–420.

Reynolds, C. W. (1987). Flocks, herds, and schools: a distributed behavioral model. *Computer Graphics*, 21(4):25–34.

Sakai, S. and Suzuki, R. (1972). A model of the schooling of fishes (in japanese). *The Institute of Electronics and Communication Engineers of Japan (IECE), MBE.*

Sakai, S. and Suzuki, R. (1973). A model for group structure and its behavior (in japanese). *The Institute of Electronics and Communication Engineers of Japan (IECE), MBE.*

Sayama, H. (2007). Decentralized control and interactive design methods for large-scale heterogeneous self-organizing swarms. In *Advances in Artificial Life*, volume 4648, pages 675–684. Springer, LNAI.

Vicsek, T. and Zafeiris, A. (2012). Collective motion. *Physics Reports*, 517:71–140.