Predator-Prey Simulation with Boid Flocking Behaviour

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1 Introduction

This simulation aims to model the dynamics of predator-prey interactions by mimicking flocking behaviour observed in bird species. Using the Boid algorithm, originally introduced by Craig Reynolds, the simulation replicates natural flocking behaviours to achieve emergent group dynamics among agents. Here, "prey" agents follow typical flocking behaviours while avoiding predator agents, which attempt to capture prey, creating a complex and dynamic interaction model. This system explores fundamental principles of flocking and predator-prey dynamics, which have applications in ecological modelling, artificial intelligence, and computer graphics.

2 Method

The simulation is based on the Boid algorithm, which is modified to incorporate predator-prey dynamics. This section describes the mathematical models behind each behaviour implemented in the simulation.

2.1 Boid Flocking Model

Each prey (boid) in the simulation follows three core behaviours: separation, alignment, and cohesion. Each behaviour is represented mathematically as a vector, and the final velocity of each prey is determined by the weighted sum of these behaviours.

Separation The separation behaviour is designed to prevent overcrowding by steering each boid away from its neighbours if they are within a certain distance. Mathematically, the separation vector $\mathbf{S_i}$ for boid i can be expressed as:

$$\mathbf{S_i} = -\sum_{j \in \text{Neighbours}(i)} \frac{\mathbf{p_j} - \mathbf{p_i}}{|\mathbf{p_j} - \mathbf{p_i}|}$$

where $\mathbf{p_j}$ and $\mathbf{p_i}$ are the positions of boid j and boid i, respectively, and Neighbours(i) denotes the set of boids within a certain separation distance of boid i.

Alignment Alignment ensures that each boid aligns its direction with nearby boids. The alignment vector $\mathbf{A_i}$ for boid i is defined as:

$$\mathbf{A_i} = \frac{1}{|\text{Neighbours}(i)|} \sum_{j \in \text{Neighbours}(i)} \mathbf{v_j}$$

where $\mathbf{v_j}$ is the velocity of boid j. This results in an averaged velocity vector that steers boid i toward the direction of its neighbours.

Cohesion Cohesion directs each boid towards the center of mass of its neighbours, promoting group clustering. The cohesion vector $\mathbf{C_i}$ for boid i is given by:

$$\mathbf{C_i} = \left(\frac{1}{|\text{Neighbours}(i)|} \sum_{j \in \text{Neighbours}(i)} \mathbf{p_j} \right) - \mathbf{p_i}$$

where the first term calculates the center of mass of the neighbouring boids, and the subtraction from $\mathbf{p_i}$ directs the boid toward this center.

Resultant Velocity The overall velocity $\mathbf{V_i}$ of each boid i is calculated by combining the three behaviours:

$$\mathbf{V_i} = w_s \mathbf{S_i} + w_a \mathbf{A_i} + w_c \mathbf{C_i}$$

where w_s, w_a, and w_c are weights that control the influence of separation, alignment, and cohesion, respectively.

2.2 Predator-Prey Interaction

In addition to the flocking behaviours, the simulation introduces a predator-prey interaction. Predators are given behaviours that enable them to seek out and approach prey, while prey boids include an additional avoidance behaviour to evade predators.

Prey Avoidance The prey avoidance behaviour is similar to separation but specifically targets the predator's position. The avoidance vector $\mathbf{A_i}^{\text{pred}}$ for each prey i relative to a predator located at $\mathbf{p}_{\text{pred}}$ is:

$$\mathbf{A_i}^{\text{pred}} = -\frac{\mathbf{p}_{\text{pred}} - \mathbf{p_i}}{|\mathbf{p}_{\text{pred}} - \mathbf{p_i}|}$$

This vector is weighted and added to the prey's overall velocity to steer it away from the predator.

Probabilistic Hawk Targeting The predator selects its target based on a probabilistic approach, where it assigns higher probabilities to prey closer to its current position. Let $P(j)$ denote the probability of targeting prey j, defined as:

$$P(j) = \frac{\exp(-|\mathbf{p_j} - \mathbf{p}_{\text{pred}}|)}{\sum_k \exp(-|\mathbf{p_k} - \mathbf{p}_{\text{pred}}|)}$$

where $\mathbf{p_j}$ and $\mathbf{p}_{\text{pred}}$ are the positions of prey j and the predator, respectively. The predator also has a slight preference for the prey it targeted in the previous step, denoted as j_{prev}, by modifying $P(j)$ as follows:

$$P(j_{\text{prev}}) = \alpha \cdot P(j_{\text{prev}})$$

where $\alpha > 1$ is a bias factor. After calculating probabilities, the predator stochastically selects a target prey k.

Murmuration Confusion When the density of prey near the predator exceeds a threshold $N_{\text{threshold}}$, the predator's targeting is disrupted, leading to erratic movements. The perturbation vector $\mathbf{\Delta P}_{\text{pred}}$ is amplified beyond this threshold:

$$\mathbf{\Delta P}_{\text{pred}} = \mathbf{R} \cdot \left(1 + \frac{N_{\text{local}} - N_{\text{threshold}}}{N_{\text{threshold}}}\right)$$

where $\mathbf{R}$ is a random vector, and N_{local} is the number of prey within a certain radius of the predator. This amplification causes the predator to lose focus, mimicking the confusion effect observed in natural murmurations.

Combined Dynamics The final positions and velocities of both prey and predator agents are updated iteratively. Each prey agent's velocity $\mathbf{V_i}$ is adjusted based on separation, alignment, cohesion, and avoidance behaviours, while the predator's velocity is influenced by probabilistic targeting and murmuration-induced perturbations. This iterative process results in emergent behaviours that reflect complex predator-prey dynamics.

References

[1] Craig W. Reynolds. (1987). *Flocks, herds and schools: A distributed behavioral model*. Proceedings of the 14th Annual Conference on Computer Graphics and Interactive Techniques, pp. 25–34. Association for Computing Machinery. doi:10.1145/37401.37406.