# Final Project Report 2026

*Spatial Simulation*
*(25W856284)*


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January 10, 2026

# Preface

## Group Composition

This project was completed by Timothy Simons and Gedeon Igelspacher.

## Division of Labor

- **Timothy Simons**: Sheep flocking dynamics, data collection, validation
- **Gedeon Igelspacher**: [Describe contributions, e.g., implementation, validation, writing sections]

## AI Statement

AI assisted tools were heavily used in this project. These tools were predominantly used for code generation and debugging. They also proved to be a source of good ideas when trying to conceptualise the simulation model.

The Large Language Models (LLMs) of choice were Anthropic's Claude and Google's Gemini models. These models showed higher proficiency in understanding GAML syntax and structure than competitors. OpenAI's ChatGPT model suffered from severe hallucinations, making it unsuitable for this project.

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# 1 Introduction

## 1.1 Background

This project develops an agent-based model of sheep herding using the GAMA platform, implementing flocking algorithms for the sheep and steering strategies observed in shepherd dogs.

## 1.2 Research Question

**Can agent-based simulation accurately represent real-world shepherd dog herding behavior?**

This research investigates whether a computational model based on geometric steering forces and flocking algorithms can replicate the complex dynamics observed when a working dog herds sheep into a pen.

Specifically, we examine whether:

- Simulated sheep exhibit comparable flocking patterns to real sheep under dog pressure
- A rule-based dog agent can produce herding strategies similar to trained shepherd dogs
- Convex hull statistics can serve as a quantitative measure of behavioral similarity between simulation and reality

By validating simulation output against drone footage of actual herding, this work explores the feasibility of using agent-based models as tools for understanding animal behavior.

# 2 Methods

## 2.1 Approach

### 2.1.1 Conceptual Model

- **Agent-Based Architecture:** The model is built on a decentralized multi-agent system (MAS) where sheep and dogs interact within a closed geometric environment.
- **Entity Definition:**
  - **Sheep:** Autonomous agents driven by modified Boids flocking rules and predator-avoidance behaviors.
  - **Dogs:** Controlling agents using geometric strategies such as Clustering, Orbiting, and Weaving to manipulate herd movement.
  - **Environment:** A spatial layout defined by vector geometries representing a starting pasture, a target pen, and a physical gate.
- **Behavioral Relationships:**
  - **Repulsion-Flight:** Dogs exert a pressure force that triggers a flight response in sheep based on proximity thresholds.
  - **Social Following:** Sheep exhibit a "follow-the-leader" mechanism, prioritizing movement toward the gate when peers are detected within the goal zone.
  - **Strict Area-Filtering:** Interaction is limited to neighbors within the same pasture to prevent artificial attraction through physical boundaries.

### 2.1.2 UML Diagram

- **Strategic Control Loop:** The diagram illustrates the dog's continuous cycle of perception, strategy selection, and geometric force calculation.
- **State Transitions:** It highlights the transition of sheep from active herd members to "secured" agents upon crossing the gate's geometric threshold.
- **Safety Logic:** Visualizes the "Emergency Retreat" mechanism designed to prevent sheep from being pinned against fences by the dog's pressure.

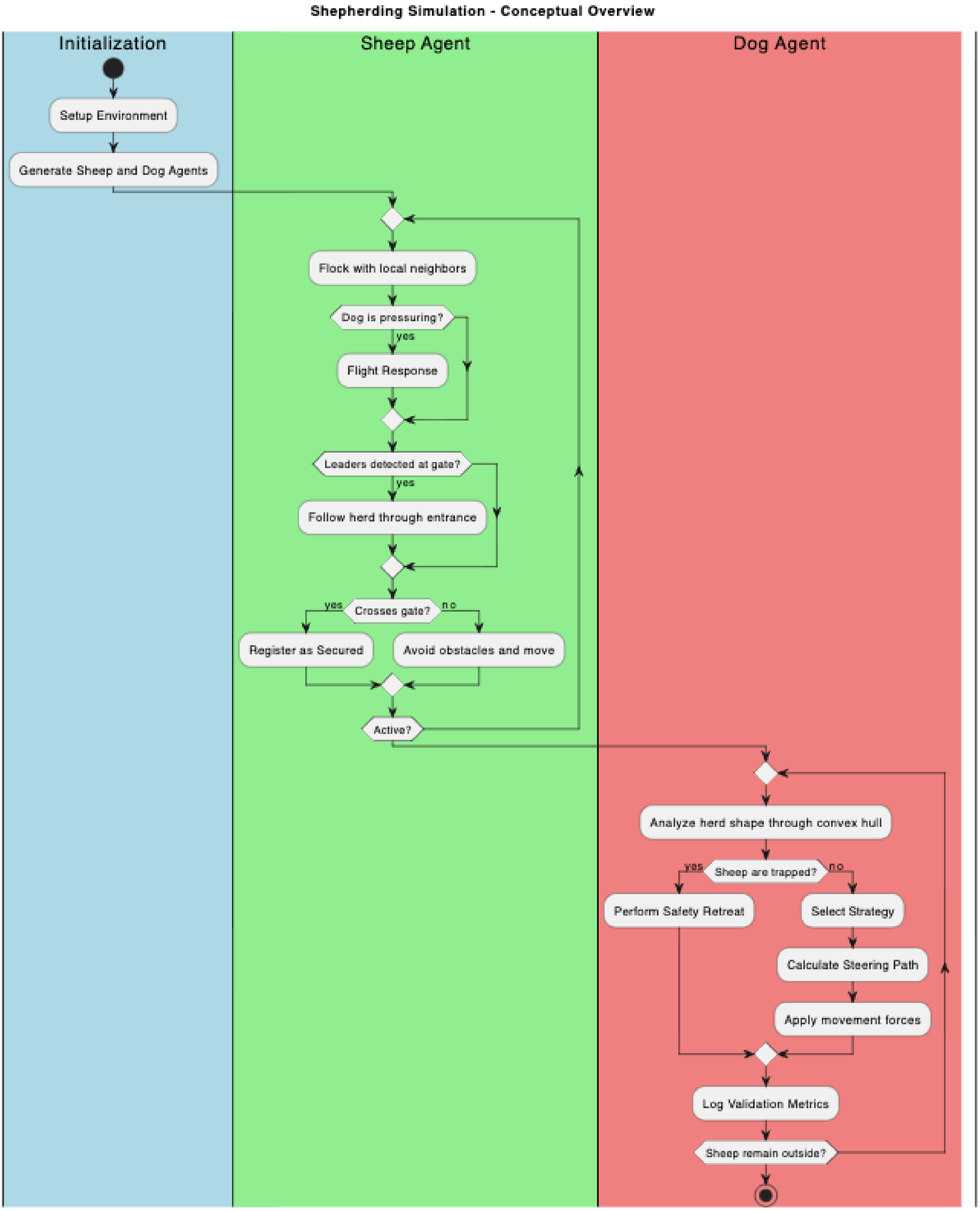


Figure 1: Conceptual UML diagram of the Shepherd model logic.

### 2.1.3 Assumptions

- **Geometric Abstraction:** Biological instincts, such as sheep exhaustion or fear levels, are simplified into mathematical steering vectors.
- **Perfect Perception:** Dogs are assumed to have global knowledge of all sheep positions to calculate the flock's convex hull and centroid accurately.
- **Homogeneous Behavior:** All sheep agents utilize identical movement parameters, assuming a uniform herd

without individual personality traits.

- **Static 2D Environment:** The terrain is modeled as a perfectly flat plane, ignoring elevation or surface friction that would naturally vary movement speed.

### 2.1.4 Calibration

To calibrate the simulation, we visually compared agent behaviour in the simulation to real-world footage of a shepherd dog herding sheep into a pen. The video contained a single dog and an assumed 400 sheep.

We iteratively modified the model parameters until the simulated sheep flock and dog behaviour mirrored the behaviour of the sheep and dog in the reference video.

The focus at this stage was on the following:

- **Flocking Dynamics**: We adjusted the sheep's separation, alignment, and cohesion parameters until the flocking behaviour in the simulation was similar to the sheep's collective movement in the video.
- **Herding Strategy**: We adjusted the simulated dog's positioning and approach to replicate the real dog's techniques.

This visual calibration confirmed the model could produce realistic dynamics before we moved on to quantitative testing and validation. The model parameters used in the calibration and validation of the simulation can be found in Table 1 in the appendix.

### 2.1.5 Validation

An attempt was made to validate the simulation using statistics derived from the convex-hull of a flock. The convex hull of the flock is a geometry defined by the smallest set of points that can completely contain all the sheep.

Figure 2: Comparison of aerial observation and geometric abstraction.

*Left:* Raw drone footage of a dog herding a flock of sheep. *Right:* Simplified representation showing the flock's centroid (green) and boundary (red convex hull) relative to the target gate (blue).

## 2.2 Implementation

The implementation is divided into three subsections. In the following we will provide information about the implementation of the environment and the agents dog and sheep.

### 2.2.1 Environment

The simulation environment consists out of distinct funtional zones defined by externally provided shapefiles, the starting pasture, the starting polygon for the herd of sheep, the target pasture and a gate that serves as the transistion between them. We faced issues by importing the original files, so we used coordinate shifting to make it work. The simulation's global shape is defined by the bounding envelope of the combined pastures, gate, and the initial sheep distribution area. For the initialization of the agents we used 400 sheep, which are randomly placed within the specific polygon *sheep_poly* inside the starting pasture. The single dog is created at an optimized position behind the flock.

### 2.2.2 Dog Species

The implementation of the `dog` species in the GAMA simulation follows a structured, strategic control loop. This architecture allows the agent to perceive the environment, select a herding strategy based on flock position, and execute movement using geometric vector steering.

**Perception and Herd Analysis**
The dog utilizes the *simple_clustering_by_distance* function with a 15 meter threshold to group sheep, which prevents confusion caused by outliers. The dog decides then on a cluster and sticks to this one until it is either herded successfully into the target area or lost, at which point the dog reevaluates the closest available group. For the chosen cluster, the dog calculates the *Convex Hull* to treat the sub-flock as a singular entity for all spatial calculations.

**Strategic Decision-Making**
In every time step, the dog evaluates the flock centroid relative to the gate location to choose one of three strategies for his behavioral states:

1. **Overshoot Recovery:** Triggered if the herd passes the gate vertically without entering; the dog positions itself to push the sheep back toward the entrance.
2. **Alignment/Flanking:** Active when the herd is horizontally misaligned ($>$ 2.0m) or far from the gate ($>$ 15.0m), applying perpendicular pressure to center the flock.
3. **Final Push:** Initiated when the herd is aligned and close, driving the sheep deep into the goal zone with tightened pressure.

**Geometric Steering and Weaving Logic**
The dog is maintaining pressure without penetrating the flock or coming too close to it through spatial logic. The dog is flanking left and right using a weave offset that narrows from 70° to 15° during the final approach to ensure control. The flanking endpoints are on the buffer contour of the convex hull around the chosen flock. If the flock exceeds an area of 200 units, the buffer grows to ensure to get all the sheep back together. If the new flanking point is more than 90° away from the current one, it will calculate some waypoints of 30° to prevent the dog from running through the herd.

**Physics and Vector Summation**
The final movement trajectory is determined by summing the steering forces, Attraction and Repulsion. The attraction force pulls the dog to the calculated target position on the flock buffer contour and the repulsion force is pushing the dog away from the edge of the flock hull to maintain the working distance and prevent collision. They have different weights, so it is more important that the dog does not run into the sheep flock than being attracted to the target point.

**Movement Execution and Constraints**
To ensure that the dog is staying in the start pasture, we implemented a fence sliding mechanism, so if the target point is calculated outside of the boundary, the position will be snapped to the closest valid point on the pasture contour. The dog is removed once all sheep are successfully secured.

### 2.2.3 Sheep Species

The sheep agents implement a modified Boids flocking algorithm through three core behavioral rules: separation, alignment, and cohesion. Each sheep maintains a velocity vector and evaluates neighbors within a 300° arc-shaped perception zone with 10-meter radius to compute steering forces.

**Collision Avoidance:** Sheep execute immediate avoidance when neighbors enter within 2.0 meters. The repulsion force is proportional to how far the neighbor has invaded the minimum distance threshold and points directly away from the intruder, preventing physical overlap.

**Separation:** Sheep accumulate repulsion from all neighbors by summing their relative positions and scaling by the separation factor (0.0002), creating gentle steering away from crowded regions.

**Alignment:** Agents adjust their velocity toward the average velocity of nearby sheep, weighted by the alignment factor (0.005), producing coordinated directional flow within the flock.

**Cohesion:** Sheep apply attraction toward the spatial centroid of their local neighborhood, weighted by the cohesion factor (0.007), maintaining group integrity and preventing fragmentation.

**Movement Execution:** Each step, sheep compute their velocity magnitude and normalize to maximum speed (0.5 m/cycle) if exceeded. The agent moves in its computed heading direction and reorients its perception arc accordingly.

# 3 Results

The statistics of the convex hull were calculated for each frame of the video and for each cycle of the simulation. The collection of these statistics is an attempt to quantify the flocking behaviour of the sheep as they are being influenced by the dog.

The convex hull statistics are calculated as follows:

- *Hull Area*: refers to the area of the hull geometry measured in $pixels^2$ or $m^2$.
- *Hull complexity*: refers to the number of vertices of the convex hull.
- *Distance from hull centroid to target gate*: is measured in $pixels$ or $m$.

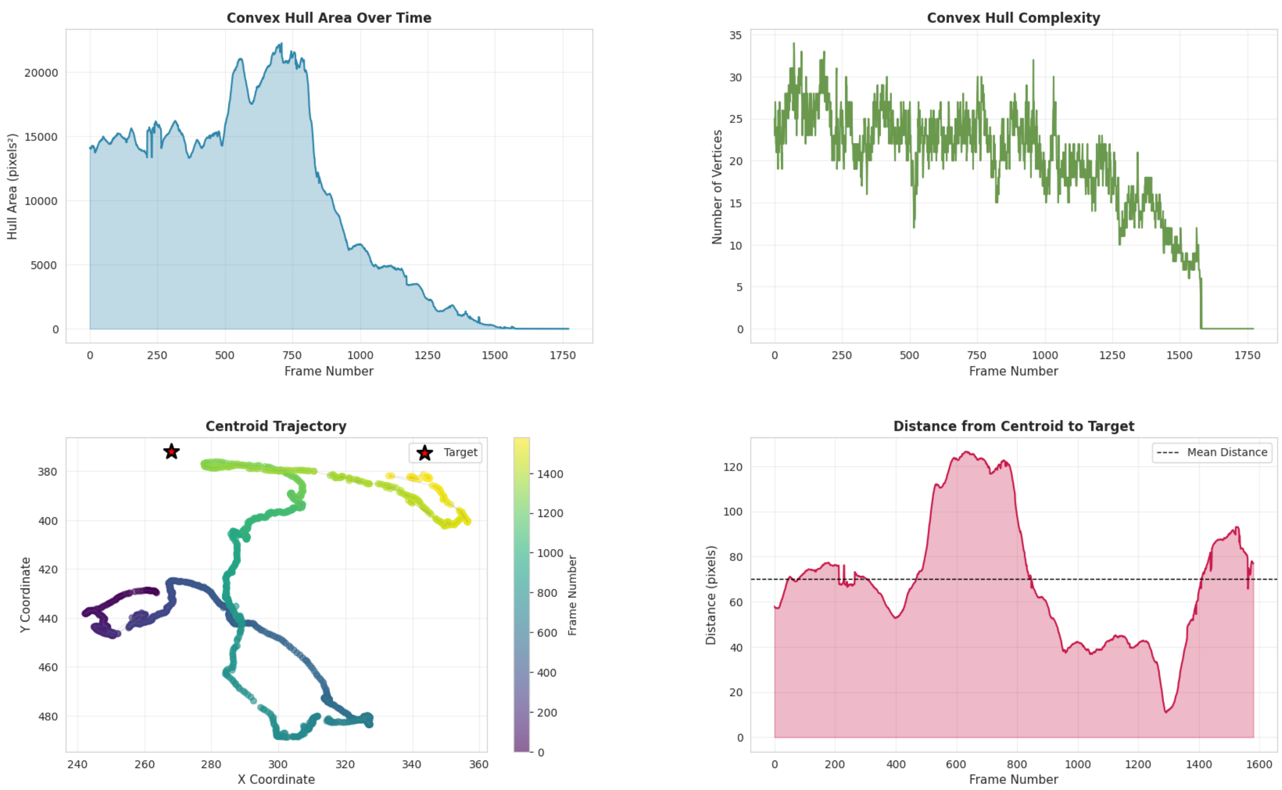


Figure 3: Convex Hull Statistics Analysis (Drone Footage)

As expected, the convex hull area and complexity decreases as the sheep get successfully herded through the gate. The centroid trajectory does not end at the target because the farmer opens a second gate at the end of the video to herd the remaining sheep. The distance of the centroid to target does not end at zero for the same reason.

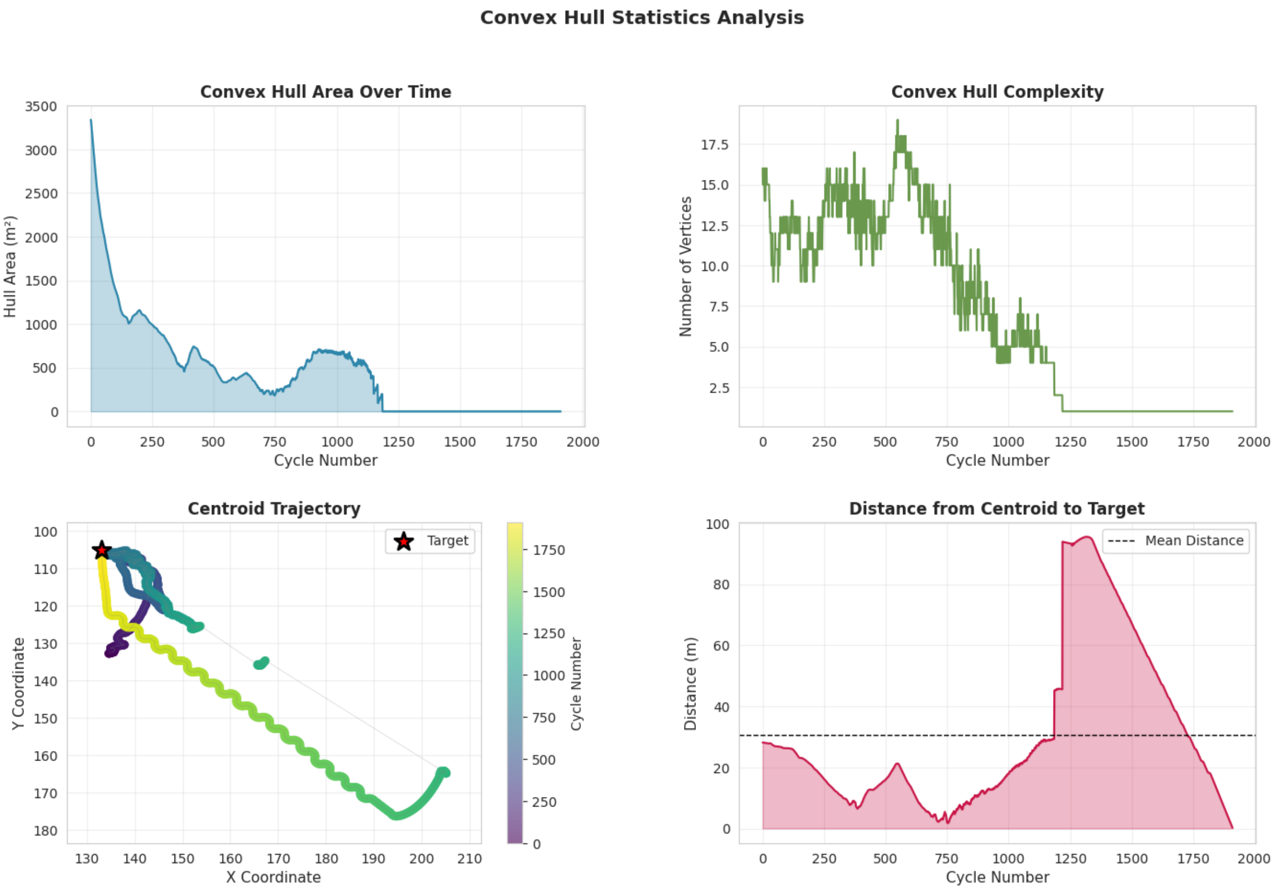


Figure 4: Convex Hull Statistics Analysis (Simulation)

The convex hull statistics of the simulation appears more erratic as the sheep get separated to individual clusters more frequently in the simulation than in the drone footage. The parameters used can be found in Table 1 in the appendix.

Current validation is limited to a visual comparison of convex hull statistics derived from a single video and a single simulation. While this confirms basic similarity between the two, a single sample cannot account for variance seen in different pastures, sheep breeds, shepherd dogs etc. Future work could include increasing the sample size of both video and simulation and then performing a comparison for statistical similarity.

# 4 Discussion

## 4.1 Limitations

**Single Reference Validation**: The model is calibrated and compared against a single drone video under specific conditions (one dog, approximately 400 sheep, particular pasture geometry). Real-world herding varies significantly across breeds, terrain types, and weather conditions—none of which are captured in this limited validation.

**Perfect Information Assumption**: The simulated dog has global knowledge of all sheep positions to calculate convex hulls and centroids. Real dogs rely on visual perception with occlusion, depth estimation errors, and attention limits that fundamentally alter decision-making.

## 4.2 Future Work

**Expanded Validation Dataset**: Collect convex hull statistics from multiple herding videos across different farms, dog breeds, and flock sizes to establish statistical confidence intervals for real-world behavior. Apply hypothesis testing (e.g., Kolmogorov-Smirnov tests) to determine if simulation distributions fall within observed ranges.

**Multi-Dog Coordination**: Extend the model to multiple dogs working cooperatively.

# 5 Conclusion

This project demonstrates that agent-based simulation can produce sheep herding behavior qualitatively similar to real-world dynamics observed in drone footage. Despite limitations, this work establishes a foundation for using computational models to study herding dynamics.

# A Model Parameters

Table 1: Parameters of the Shepherd Simulation Model

| Parameter | Value | Description |
|---|---|---|
| *Flocking Behavior* | | |
| Separation strength | 0.0002 | Strength of separation from nearby sheep |
| Velocity alignment strength | 0.005 | Strength of velocity alignment with neighbors |
| Cohesion strength | 0.007 | Strength of attraction to herd center |
| *Gate Behavior* | | |
| Gate awareness distance | 10.0 m | Distance at which sheep detect the gate |
| Gate attraction strength | 0.8 | Strength of attraction toward gate center |
| Herd gate speed bonus | 0.3 | Speed bonus when herd moves toward gate |
| Channeling distance | 15.0 m | Distance for funneling sheep to gate |
| *Sheep Movement* | | |
| Maximum velocity | 0.3 | Maximum speed of sheep |
| Minimum distance between sheep | 2.3 m | Minimum distance between individual sheep |
| Fence detection distance | 3.0 m | Distance at which sheep detect fence |
| Fence slide strength | 1.5 | Strength of sliding along fence |
| Flight distance from dog | 25.0 m | Distance triggering flight from dog |
| Flight response strength | 3.0 | Strength of flight response from dog |
| *Dog Strategy* | | |
| Working distance from herd | 10.0 m | Operating distance from sheep herd |
| Maximum dog speed | 10.0 | Maximum speed of dog |
| Minimum commitment duration | 150 cycles | Minimum cycles dog commits to cluster |
| Cluster completion threshold | 5.0 m | Distance to consider cluster complete |
| Maximum cluster distance | 20.0 m | Maximum distance for clustering sheep |
| Weave width angle | 60.0° | Base angle for weaving pattern |
| *Simulation Setup* | | |
| Total number of sheep | 400 | Total number of sheep in simulation |