KTH Computer Science
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Extending Reynolds' flocking model to a simulation of sheep in the presence of a predator

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Abstract

Reynolds' flocking model is a widely used behavioral model, originally made for simulating flocks of birds. In this study we examine the possibility of modifying the model to simulate the scenario of a flock of sheep in the presence of a predator. Apart from introducing a human-controlled predator, the simulated animals were modified to move in two instead of three dimensions and behave like sheep instead of birds. A simulator, using this modified version of Reynolds' model, was implemented so that the behavior of the simulated sheep could be compared to the behavior of real sheep. The comparison was done primarily by using quantitative data gathered from the simulator. This comparison showed the existance of several similarities between the simulated sheep and real sheep. These results suggest that Reynolds' flocking model can be used as a basis for this scenario.

Referat

Reynolds flockmodell är en välanvänd beteendemodell som från början skapades för simulera en fågelflock. I den här rapporten undersöker vi om det är möjligt att modifiera modellen så att den simulerar scenariot med en fårflock i närheten av ett rovdjur. Förutom att introducera ett människo-styrt rovdjur, ändrades även de modellerade djuren till att röra sig i två dimensioner istället för tre, och bete sig som får istället för fåglar. En simulator, som använde den modifierade versionen av Reynolds flockmodell, implementerades för att jämföra beteendet hos de simulerade fåren med riktiga fårs beteende. Jämförelsen gjordes primärt med hjälp av kvantitativ data från simulatorn. Jämförelsen visade att det fanns ett antal likheter mellan de simulerade fåren och riktiga får. Dessa resultat tyder på att Reynolds flockmodell kan användas som grund för detta scenario.

Contents

Chapter 1

Introduction

Computer simulations are today invaluable in a wide variety of fields, ranging from fluid dynamics [1] to traffic control [2]. Additionally, Steven Strogatz of Cornell University argues that as science and mathematics progresses, the need for simulations increases [3]. He points out there's a trend where it becomes harder to understand the *why* behind newly discovered theorems. Even when failing to understand, computer simulations can be used to observe results and behaviors, and thus draw conclusions. These trends indicate that advances in the field of simulation today could result in advances in many other fields as well. More importantly, computer simulations may even become a necessity for progress in some fields in the future. Therefore research in computer simulations may be important for the advances of science as a whole.

1.1 Reynolds' flocking model

In this report we will discuss the simulation of flocking behavior. One flocking model in particular, Reynolds' flocking model, will be discussed. The model was developed in 1987 by Craig Reynolds. [4].

Reynolds model consists of a set of simple rules that accurately model the complex behavior of a flock. The rules are applied separately to each individual in the flock, portraying the autonomy of the real animals. Reynolds used the model to simulate flocks of birds, but the model has been applied to other scenarios as well, such as a bat swarm in the movie Batman Returns (1992) and a wildebeest stampede in the movie Lion King (1994) [5].

The aim of this study was to examine whether Reynolds' flocking model could be extended to simulate a flock of sheep reacting to the presence of a human-controlled predator. This new scenario requires three modifications to Reynolds' original flocking model: a dimension reduction from three to two, a change of simulated animal from bird to sheep and an addition of a human-controlled predator that the sheep react to.

1.2 Problem Statement

In this project a simulator based on Reynolds' flocking model was implemented, which assisted in answering three questions:

Can Reynolds' model be modified to work well with two dimensions? This is a modification of Reynolds' model, which was made for simulations in three dimensions [4].

Can Reynolds' model be modified to work well with sheep instead of birds? Sheep's flocking behavior differs from birds' in that they are not constantly in motion. Reynolds' model creates a tendency that never allows the birds to be still [4]. The model needs to be modified to remove this tendency.

Can Reynolds' model be modified to work well with the introduction of a predator? The original model neither contained anything similar to a predator [4] nor seemed to take into account the possibility of adding one. The model needs to be modified to incorporate the sheep's reaction to the predator.

1.3 Purpose

Evaluating Reynolds' model for a different scenario than it was originally intended for may serve a number of purposes.

The primary purpose is to provide information on how Reynolds' flocking model holds up to modifications. This information can be used to determine if Reynolds' model can serve as a basis for future projects involving simulations of flocking behavior in a scenario similar to the one discussed here.

Another potential purpose is to provide information on how to implement a similar simulator. The implementation described in this report may be used as a basis for future projects. A third purpose is that a correctly modeled sheep simulator will allow users to visually understand how the flocking behavior of sheep works in the presence of a predator or a herding dog.

Chapter 2

Background

In this chapter, background information on animal behavior as well as flocking simulations is presented. A central part of this project is Reynolds' model, upon which the modified model is based. A description of Reynolds' model can be found in the section Flocking simulations.

2.1 Animal behavior

Flocking animals have a flight zone, which is an area with a certain radius around the sheep. If a perceived threat, such as a predator or a herding dog, approaches the flight zone, the flock animal will usually face the threat. If the threat enters the radius of the flight zone, the animal will try to flee. The size of the flight zone is dependent on the animal and how used it is to having strange objects moving close to it. Specifically, sheep are a domesticated animal and are often in the presence of a perceived threat (the herding dog) and thus have a relatively small flight zone [6]. Sheep display typical flocking behavior when in groups of five or more sheep [7].

A study done by King measured the cohesion of a flock of sheep in the presence of a perceived threat, in this case a herding dog [8]. The dog was instructed to "herd a flock of initially resting sheep to a target zone with minimal guidance" [8]. The position of each animal was measured using GPS trackers. Data, from three separate herding events, showed that when under threat sheep tend to move towards the center of the flock. It also showed that the 46 sheep's mean distance to the flock centroid stabilized at about four meters when the dog was close.

2.2 Flocking simulations

Simulating a group of objects can be done at different levels, identified by Parent as particle systems, flocks and autonomous behavior [9]. Simulations of particle systems take in account only a set of physical rules, which are strictly followed. Autonomous behavior on the other hand allows each individual entity to act intelligently and independently. A combination of the two is flocks, which follow a set of rules which make them act in self-interest, e.g. avoiding threats and staying with the group.

Flocking behavior can be simulated with a simple and remarkably accurate model consisting of three basic rules, as described by Reynolds in 1987 [4]. The first of these rules is Cohesion, which handles flock centering – a bird will regard the position of nearby birds and try to stay close to the average position of them. The second rule is Separation, which handles collision avoidance – a bird will regard the distance to nearby birds and if they are too close, steer away to avoid collision. The third rule is Alignment, which handles velocity matching – a bird will regard the distance and velocity of nearby birds, and match its velocity to them. Consequently, individual birds choose their own course affected by the velocity and position of nearby birds. All three rules take into account the distance of nearby birds to calculate the resulting velocity. The relevance of regarded birds is weighted with respect to the inverse square of the distance between them. This way, birds that are outside a certain radius are in practice invisible.

Reynolds' model is originally designed for three dimensions, but due to the fact that the model allows each object to only be aware of objects within a certain radius Reynolds claims that his model "is actually a better model of a school or a herd rather than a flock" [4]. This is due to the fact that schools and herds block each other's view, limiting the field of vision in accordance to the model, whereas birds have great long-range vision and are in practice able to see the entire flock.

To use Reynolds' model in a scenario where the flock needs to react to the presence of a predator, modifications to the model are needed. In a report by Delgado-Mata, an additional rule, Escape, is proposed that creates the reaction needed [10]. Furthermore the model proposed by Delgado-Mata also provides each animal with emotions that further affect how they react. The emotions spread through the flock through pheromones. The emotions control the individual strength of the rules. Delgado-Mata only implemented the emotion fear. The more fear that affects an animal, the more it wants to stay together with the group and escape from a potential threat.

Chapter 3

Approach

In this chapter, details about the modified Reynolds' model, the implementation of it and the study conducted are presented. The section Model is divided into several subsections describing a certain part of the model. The model, including multipliers, was derived from a combination of trial and error and knowledge of the sheep behavior described in the chapter Background. For similarities to Reynolds' model and further motivation of the model, see the chapter Discussion.

After the section Model, comes the section Implementation which describes how the model was implemented in Java. The section Study describes the study that was conducted with the purpose of evaluating the realism of the simulator.

3.1 Model

The modified model is based on Reynolds' three rules - Cohesion, Separation, Alignment. In addition to these rules the Escape rule was added, in accordance to Delgado-Mata's article [10]. All four rules are applied individually for each sheep. Each separate rule results in a vector that describes the sheep's suggested velocity. Weighting the vectors from these rules together with two sets of multipliers results in the final velocity vector.

3.1.1 Multipliers

The vectors corresponding to each of Reynolds' rules are weighted with two different multipliers that decide how strong the respective rules are. Both of the sets of multipliers weigh the importance of the rules relative to each other. The first multiplier is the base multiplier, and the only one used when the predator is not present. When the predator approaches the sheep, the second multiplier increases in strength. This causes the rules to be weighted differently with respect to each other, depending on the distance to the predator. The variation in strength of the second multiplier is described by a sigmoid function. This function, seen in Formula (3.1), is referred to as p throughout the text.

$$p(x) = \frac{1}{\pi} \arctan\left(\frac{r - x}{20}\right) + 0.5 \tag{3.1}$$

where x is the distance from the sheep to the predator and r is the value of x where the absolute derivate of $p(x)$ is the largest. This distance r represents the flight zone radius of the sheep.

The rule that was added to Reynolds' model, Escape, is weighted with only one multiplier since it is active only when the predator is present.

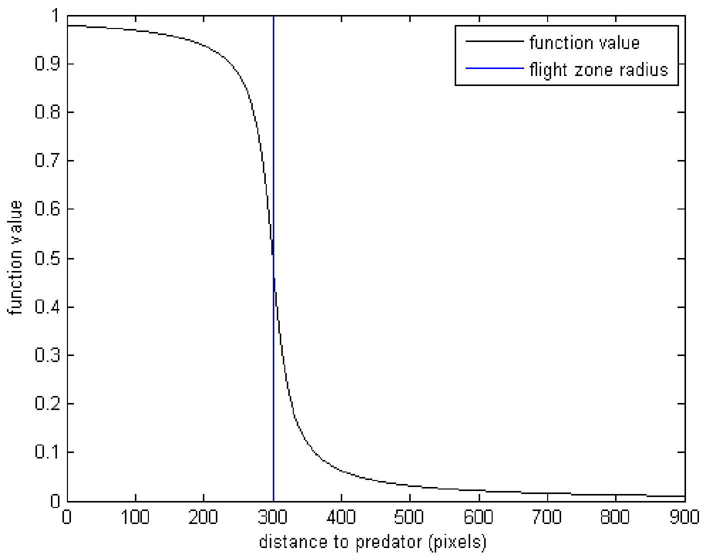

Figure 3.1: The sigmoid function used to modify the predator multiplier

Figure 3.1 depicts the function p, with the flight zone radius $r = 300$. It can be seen in the figure that the sigmoid function value goes from 0 to 1 as the distance x decreases. This allows for a smooth transition from a state where the second multiplier is of little significance to a state where it is in full effect when the predator is moving closer.

Each rule has two corresponding multipliers that determine the strength of the rule. The formula for combining these two multipliers can be seen in (3.2).

$$m(1 + p(x)m_p) \tag{3.2}$$

where m is the first multiplier and m_p is the second multiplier of the rule.

3.1.2 Inverse square function

In two of the rules, Separation and Escape, nearby objects are prioritized higher than those further away. This prioritization is described by an inverse square function. This function, seen in Formula (3.3), is referred to as *inv* throughout the text.

$$inv(x, s) = \left(\frac{x}{s} + \varepsilon\right)^{-2} \tag{3.3}$$

where x is the distance between the objects, s is a softness factor that slows down the rapid decrease of the function value and ε is a small value used to avoid division by zero, when $x = 0$.

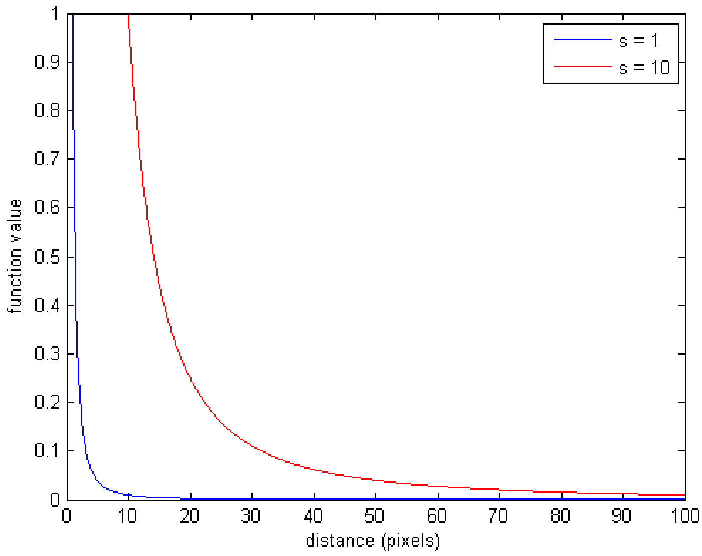

Figure 3.2: The inverse square function *inv*

Figure 3.2 depicts the inverse square function plotted with two different softness factors. The two curves in the figure correspond to the softness factor used in the two rules, $s = 1$ for Separation and $s = 10$ for Escape. Regardless of softness factor it is visible in the figure that the function value grows considerably as the distance decreases.

3.1.3 Cohesion rule

The Cohesion rule is calculated for each sheep s with position $\mathbf{s}_p$. The Cohesion vector $\mathbf{coh}(s)$ is directed towards the average position $\mathbf{S}_p$. The rule vector is calculated with the function

$$\mathbf{coh}(s) = \frac{\mathbf{S}_p - \mathbf{s}_p}{|\mathbf{S}_p - \mathbf{s}_p|} \tag{3.4}$$

3.1.4 Separation rule

The Separation rule is calculated for each sheep s with position $\mathbf{s}_p$. The contribution of each nearby sheep s_i is determined by the inverse square function of the distance between the sheep with a softness factor of 1. This function can be seen in Formula (3.3). The rule vector is directed away from the sheep and calculated with the function

$$\mathbf{sep}(s) = \sum_{i}^{n} \left(\frac{\mathbf{s}_p - \mathbf{s}_{ip}}{|\mathbf{s}_p - \mathbf{s}_{ip}|} inv(|\mathbf{s}_p - \mathbf{s}_{ip}|, 1) \right) \tag{3.5}$$

3.1.5 Alignment rule

The Alignment rule is calculated for each sheep s. Each sheep s_i within a radius of 50 pixels has a velocity $\mathbf{s}_{iv}$ that contributes equally to the final rule vector. The size of the rule vector is determined by the velocity of all nearby sheep N. The vector is directed in the average direction of the nearby sheep. The rule vector is calculated with the function

$$\mathbf{ali}(s) = \sum_{s_i \in N} \mathbf{s}_{iv} \tag{3.6}$$

where

$$N = \{s_i : s_i \in S \cap |\mathbf{s}_{ip} - \mathbf{s}_p| \leq 50\} \tag{3.7}$$

3.1.6 Escape rule

The Escape rule is calculated for each sheep s with a position $\mathbf{s}_p$. The size of the rule vector is determined by inverse square function (3.3) of the distance between the sheep and predator p with a softness factor of 10. The rule vector is directed away from the predator and is calculated with the function

$$\mathbf{esc}(s) = \frac{\mathbf{s}_p - \mathbf{p}_p}{|\mathbf{s}_p - \mathbf{p}_p|} inv(|\mathbf{s}_p - \mathbf{p}_p|, 10) \tag{3.8}$$

3.1.7 Weighting the rules

Each sheep's final velocity vector **v** is the weighted sum of all the four rule vectors calculated for this sheep. Each of Reynolds' original rules are weighted with the combination of its two corresponding multipliers, whereas the Escape rule is weighted only with one, as seen in Formula (3.2).

$$\begin{aligned} \mathbf{v} = m_c(1 + p(x)m_{cp})\mathbf{coh}(s)+ \\ +m_s(1 + p(x)m_{sp})\mathbf{sep}(s)+ \\ +m_a(1 + p(x)m_{ap})\mathbf{ali}(s)+ \\ +m_e\mathbf{esc}(s) \end{aligned} \tag{3.9}$$

This final velocity vector is capped to a certain value v_{max} that represents the sheep's maximum velocity. v_{max} increases as the predator approaches. If the final velocity vector is below a certain threshold v_{min} it is set to zero. The vector is also set to zero if it is directed at a point behind the sheep, as the sheep can only turn at a certain angular velocity.

3.2 Implementation

The modified Reynolds flocking model was implemented in Java using the Swing graphics library [11]. The scene for the game consists of the background, a flock of sheep sheep and the predator. The scene is created using a JPanel of size 1000 x 600 pixels. The scene is updated with a new frame 20 times per second. Four steps are done each time frame:

1. The velocities of all animals are calculated
2. The positions of all animals are updated by adding the velocities to the current positions
3. The animals are drawn on the canvas
4. The positions of the sheep and the predator are logged to a file

In order to evaluate the logged data, MATLAB was used. A script was written to read the log file and plot the desired quantitative data.

3.3 Study

A study was conducted using the simulator, attempting to mimic King's study of GPS tracked sheep. As in King's study 46 sheep were used [8]. The predator was spawned far away from the sheep ensuring the sheep are initially at rest. The predator was then moved in a straight line towards the flock, causing the flock to gather and attempt to flee from the predator. For each time frame of the simulator, the position of the predator and all the sheep was saved. This data was used to measure cohesion of the flock of sheep relative to how close the predator was to the flock centroid. Additionally, the mean velocity of the sheep relative to how close the predator was to the flock centroid was measured.

Chapter 4

Results

In this chapter, example scenarios of the resulting simulator and quantitative data gathered from the log file are presented.

4.1 Scenarios

The figures in this section depict the simulator. The predator is shown as a large black dot. The sheep are shown as white dots with their direction indicated by a smaller black dot.

4.1.1 Without a predator

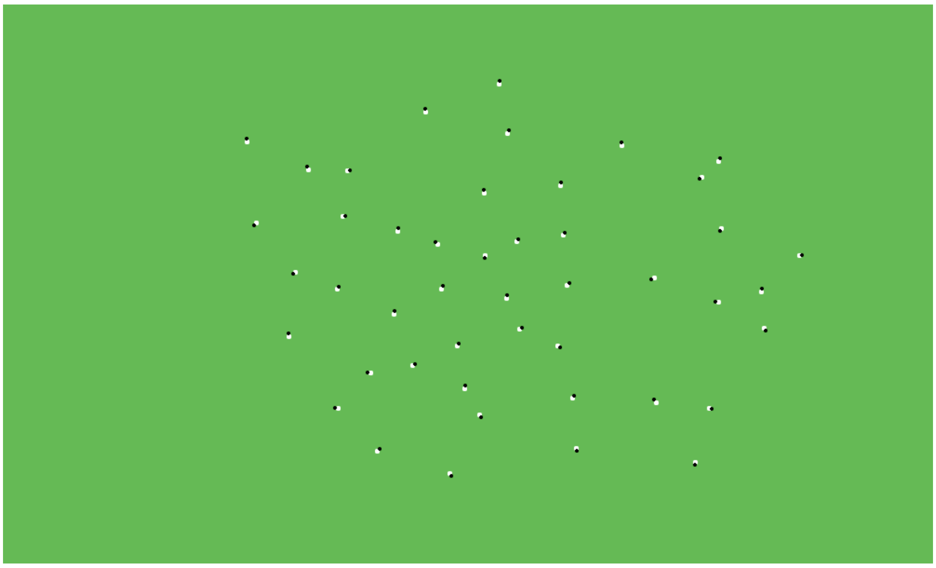

Figure 4.1: The sheep when not in the presence of a predator

With no predator nearby the sheep are spread out across the field. Their positions converge to a stable state. Figure 4.1 shows the sheep when they are not in the presence of a predator. Notice how the sheep have formed a fairly circular flock due to the Cohesion rule. Additionally the Separation rule ensures that a fair distance separates the sheep from each other. The sheep are stationary and they are not all facing the same directions.

4.1.2 Predator approaching the flock

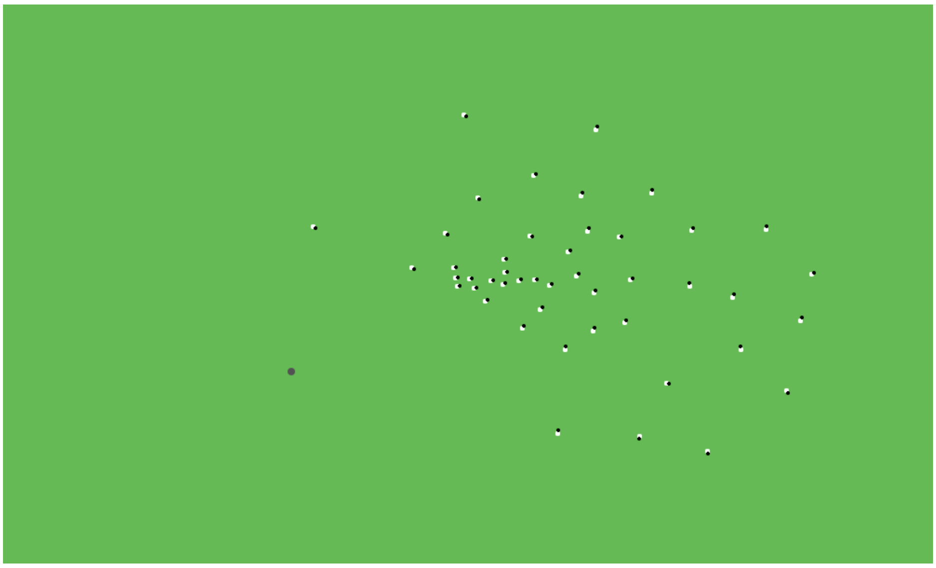

Figure 4.2: The sheep being approached by a predator

As the predator approaches, the sheep's cohesion increases. The sheep close to the predator will start moving toward the flock centroid, away from the predator. The sheep far away from the predator will also start moving due to the fact that the other sheep have come closer, which makes the Separation rule take effect. Figure 4.2 shows the sheep moving toward the flock centroid as the predator comes closer. Notice how the sheep close to the predator all are faced towards the center of the flock, whereas the sheep that do not yet "see" the predator are facing other directions. The distance between the sheep also decreases considerably compared to when the predator was not present.

4.1.3 Predator herding the flock

When the predator is herding the sheep, they form a tight group where each sheep is as close as possible to the flock centroid, while still avoiding collision with other sheep. In Figure 4.3 the sheep can be seen moving away from the predator. Note how the sheep are running in the same direction, even though it may not be the optimal direction for an individual sheep. This is due to the Alignment rule, which increases

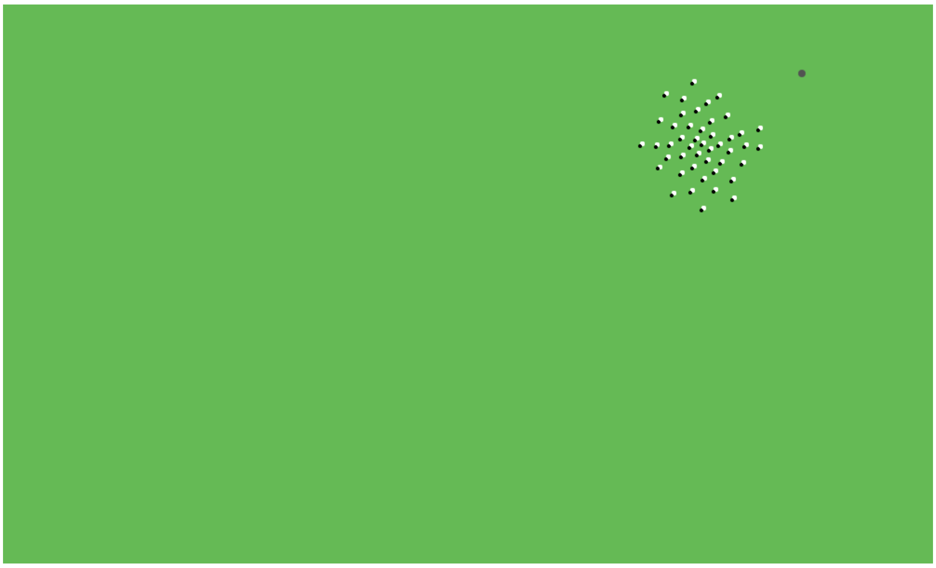

Figure 4.3: The sheep being herded by a predator

the sheep's tendency to move in the same direction as nearby sheep. Additionally note how cohesive the group is compared to when the predator was not present.

4.1.4 Predator inside the flock

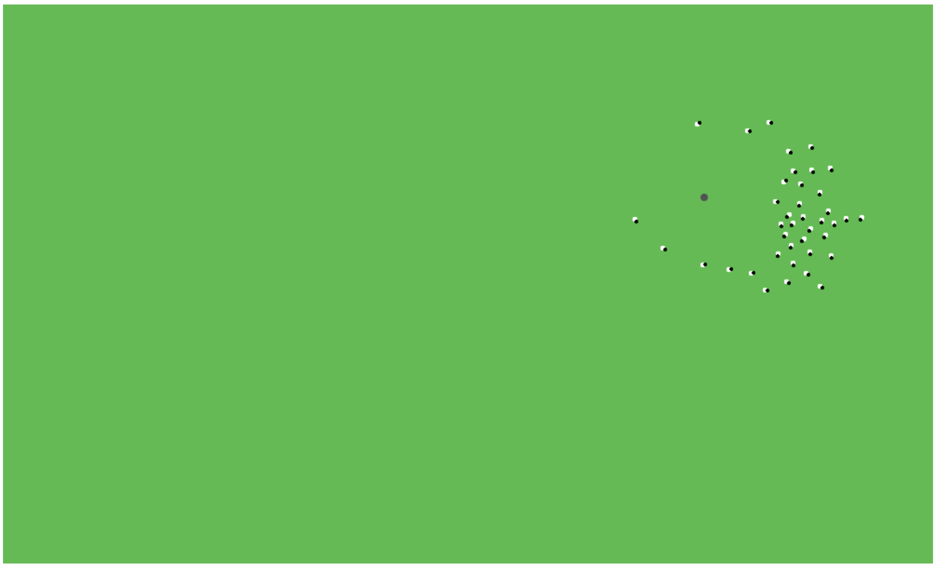

Figure 4.4: The predator being inside the flock of sheep

When the predator is close to the flock centroid, the sheep spread out in a circle-like pattern around the predator to avoid it, while still remaining close to the centroid. Figure 4.4 shows the predator when close to the flock centroid. The sheep that are away from the “main” flock are moving towards it while maintaining a safe distance to the predator.

4.1.5 A separated sheep

Figure 4.5: One sheep being separated from the flock by the predator

When a sheep is separated from the group by the predator the sheep will try to move back to the flock, due to Cohesion. However the Escape rule is much stronger than the Cohesion rule, thus the sheep will prioritize avoiding the predator. Figure 4.5 shows a sheep that is separated from the group by the predator.

4.2 Study

The study conducted showed that the flock gathered close when a predator approached. In Figure 4.6 it is visible that the cohesion increases as the predator moves closer. There is a gradual but steep transition from a separated state when the predator is not present to a cohesive state when the predator is close to the flock centroid.

The study also showed an increase in mean speed of the sheep as the predator approached. Figure 4.7 shows the sheep's velocity increasing as the predator moves closer to the flock centroid. At the start of plot the movement of the sheep is near zero, since they have converged to a stable state. As the predator moves closer more and more sheep start to move away from the predator, increasing the mean velocity.

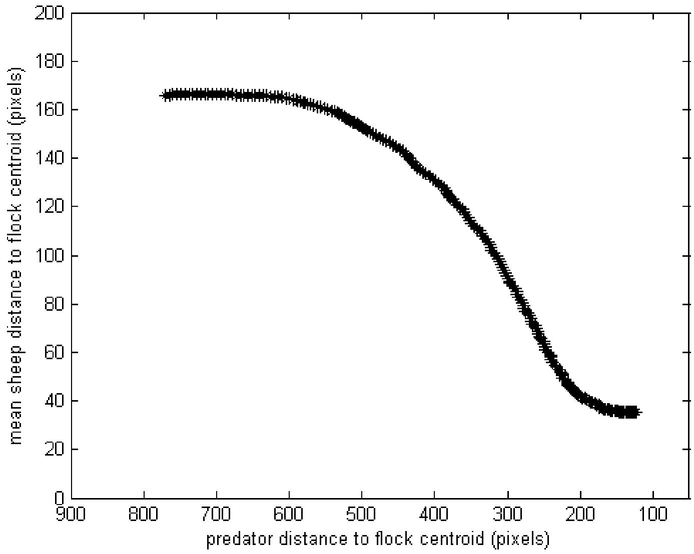

Figure 4.6: Change in mean sheep distance to flock centroid as the predator moves closer

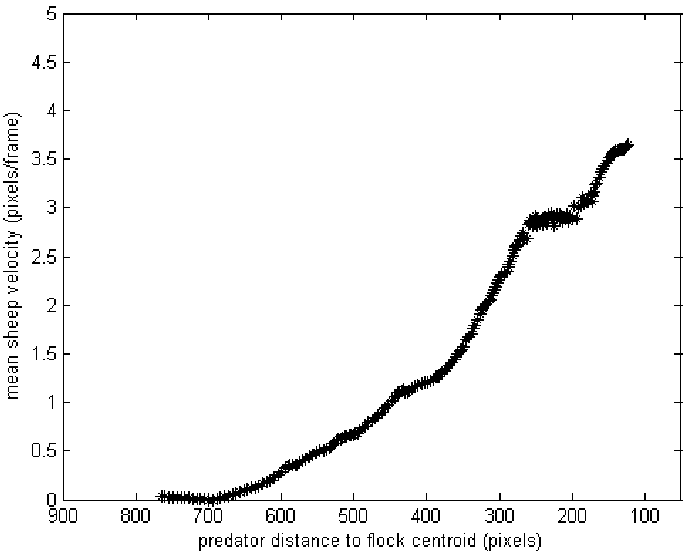

Figure 4.7: Change in sheep velocity as the predator moves closer

Chapter 5

Discussion

In this chapter, there is a discussion of the resulting implementation and answers to the problems stated in the introduction.

Our problem statement consisted of three questions:

- Can Reynolds' model be modified to work well with two dimensions?
- Can Reynolds' model be modified to work well with sheep instead of birds?
- Can Reynolds' model be modified to work well with the introduction of a predator?

All of these questions relate to how well Reynolds' model works as a basis for modifications.

These questions were answered by implementing a simulator. The reason for implementing a simulator was to get quantitative and qualitative data of our model's performance. This data could then be compared with that of a real flock of sheep.

5.1 Similarity to Reynolds' flocking model

In this section we compare the similarities between Reynolds' model and our modified model. What we used from Reynolds' article are the three basic rules that describe flock behavior.

The Cohesion rule is implemented as described by Reynolds except for one difference – in our model a sheep can see all of the other sheep, whereas in Reynolds model they are only able to see within a certain radius. When using a limited visual range, as in Reynolds' model, the sheep did not converge to a stable state but rather moved constantly.

The Separation rule is implemented as described by Reynolds. Some implementations of Reynolds' model use a hard threshold distance, that determines whether to use the Separation rule [12]. We however used an inverse square function as suggested by Reynolds [4]. The inverse square function ensures that sheep at a certain distance do not noticeably affect the rule vector. Since the contribution for a specific sheep should be inversely proportional to the square of the distance, the difference vector is normalized as seen in Formula (3.5). This normalization is not mentioned by Reynolds in his article, but ensures that the difference vector only describes the direction and not the strength. Additionally the normalization ensures that the dissipation of strength is linear instead of square.

The Alignment rule is implemented as described by Reynolds. In our model the relative importance of the Alignment rule is low. The reason why the rule is weak in our model is because Alignment causes the animals to be more prone to constant motion. This is desirable when modeling birds, but not sheep. However when the sheep are in motion, due to being herded by a predator, increasing the strength of the Alignment rule made the group move more consistently. The consistent movement made the group less prone to split up into smaller groups.

The Escape rule does not exist in Reynolds' model at all, and is therefore the largest modification by far. This rule causes the sheep to flee from the predator. In addition to adding this rule, the other rules have to be modified when the predator is present. The reason for modifying the rules is because sheep behave differently when a predator is present, as described in the chapter Background. The change in strength of the rules was done by the use of a second set of multipliers, m_{cp}, m_{sp} and m_{ap}, as seen in Formula (3.9). The second set of multipliers represents the fear emotion, as implemented by Delgado-Mata [10]. The rule that is primarily modified by the second set of multipliers is the Cohesion rule as can be seen in Figure 5.1. This change in cohesion was based on the results of King's report [8].

The escape behavior is activated when the predator enters the flight zone of the sheep. Since this flight zone has a specific radius, we wanted to set it to a threshold distance. However using a threshold distance made the sheep quickly alternate between fleeing and not being aware of the predator. Making the change in emotion follow the sigmoidal curves seen in Figure 5.1, solved this problem while maintaining a specific radius of the flight zone. The emotion of the sheep in our model is only affected by the distance to the predator, while Delgado-Mata also used pheromones to transmit emotions between the flock animals [10]. To keep our model simple, pheromones were not added.

The rules in Reynolds' model are described by three-dimensional vectors since Reynolds models birds, which move in three dimensions. Since we model sheep which move in two dimensions, we reduced the size of the vectors to two dimensions. This modification did not affect the rules in any other way.

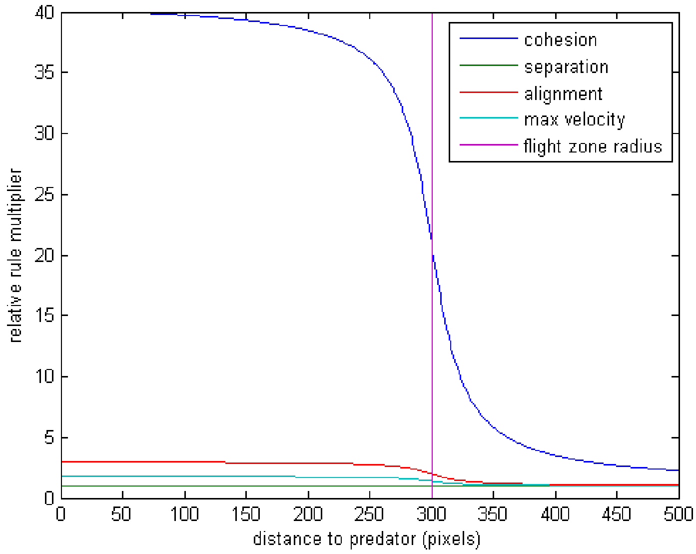

Figure 5.1: Relative increase of multipliers

5.2 Realism

In order to attempt to answer the questions in the problem statement objectively, we compared our simulation to an experiment done by King [8]. This comparison was done by plotting quantitative data from our simulation and comparing it to the plots in King's report. The plots from King and our corresponding plot are shown in Figure 5.2, which depict mean sheep distance to flock centroid relative to distance of the dog to the flock centroid. Due to the deterministic nature of our simulator, only one plot from our experiments is included while King conducted three different experiments. The scales on the plot differ, as King uses meters and our plot uses pixels.

Certain similarities can be found between the shape of our plot and King's. In both studies it is visible that when the predator is outside a certain radius the sheep do not react to it. This radius is presumably the flight zone [6], as described in the chapter Background. When the predator comes inside the flight zone the flock of sheep become more cohesive, finally stabilizing at a certain mean distance as the predator moves closer.

The ratio of mean distance to flock centroid between the initial state and the completely cohesive state of King's first two plots is approximately $\frac{32}{4} = 8$ and $\frac{22}{4} = 5.5$. The corresponding ratio for our model is $\frac{165}{35} = 4.7$. While the ratio for our model is slightly lower than the results observed by King's, the ratio is still of the same order of magnitude. One reason why the ratio of our model is lower may be because

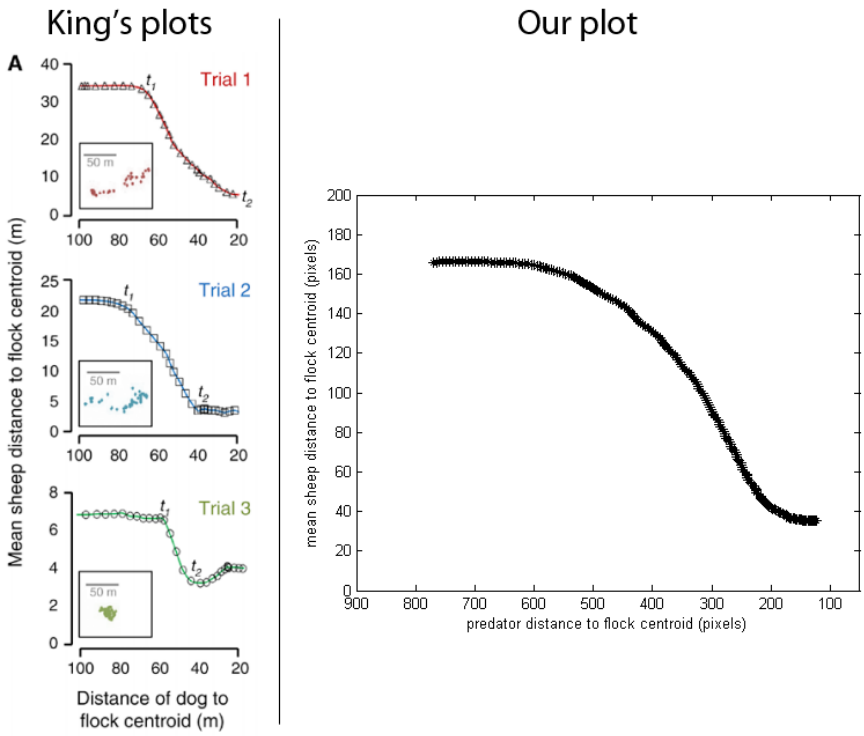

Figure 5.2: A side by side comparison of King's plots [13] and our plot from Figure 4.6

the original separation of the sheep is low. This may be because of the limited area of the simulator's window.

The results seen in the study of the sheep's velocity during the same experiment indicate that the sheep move faster when the predator is closer. This is partly due to the fact that more and more sheep start fleeing from the predator, and partly due to the fact that the maximum velocity v_{max} increases as the predator comes closer. This is expected since sheep do not move at full speed when grazing, but run fast when needed.

Sheep tend to form a circle around the perceived threat when it is in the middle of the flock. This behavior can be seen in Figure 5.3. This behavior is also displayed in our simulator as seen in Figure 4.4, even though we did not explicitly implement it. The reason the simulated sheep form a circle seems to be that the strength of the Cohesion rule is equal to the strength of the Escape rule at a certain radius from the predator. The fact that this behavior was displayed by the simulated sheep indicates that the model works well.

Another indication that model is good is that the sheep display behavior seemingly

Figure 5.3: Sheep forming a circle around a perceived threat [14].

more sheep-like than bird-like. In our model, unlike Reynolds', the animals are not constantly in motion. When stationary the animals also do not all face the same direction, as seen in Figure 4.1.

5.3 Criticism and further research

In the problem statement, the term "work well" is used for all of the questions. The term is ambiguous and thus a conclusive answer can never be found for the problem statement in its current form. Including a number of criteria the simulator should fulfill to be considered working well may be a more scientific approach to the problem.

In addition to the reformulation of the problem statement, a simulator strictly following Reynolds flocking model should have been implemented first. This implementation should then have been compared to Reynolds' implementation, and it should have been ensured that they both behave identically. Having determined identical behavior, we could then have implemented our modifications one at a time. Following this procedure we could have more conclusively answered our problem statement, since we would have eliminated some potential sources of error. In case of failure to base our model on Reynolds' model, it would be more convincing that Reynolds' model was inadequate. In case of success, it would be more convincing that a proper implementation of Reynolds' model is a good basis for simulating the discussed scenario of sheep and a predator.

When comparing our model to the results of King's study we did not know the exact movement pattern of the herding dog in King's study. Since King's plots were dependent on distance of the dog to the flock centroid rather than time, we made the assumption that we did not need to replicate the exact movement pattern of the herding dog. Instead the predator was moved in a straight line towards the flock. If this assumption was not valid, the findings from the comparison would be of no value.

Apart from improving the study conducted here, the model could also be extended. This could be done by including additional sheep behaviors. One such behavior is the tendency of sheep to turn toward the predator when the predator is approaching the flight zone. To extend the model even further more emotions than fear could be added, and obstacles and uneven topography could be added to the terrain.

Chapter 6

Conclusions

It can be concluded that Reynolds' model can be modified to work well with two dimensions instead of three. The modification to the actual model is a minor one, where two-dimensional vectors are used instead of three-dimensional ones. Our results indicate that the model can be used to simulate the behavior of animals that move in two dimensions.

The simulator based on our modified model indicates that Reynolds' model can be modified to work well with sheep instead of birds. The simulated flock shows some sheep-like behavior. The flock does not move constantly, like the birds in Reynolds model do, but are more prone to be stationary. Additionally the sheep do not always face the same direction, like the moving birds in Reynolds model do.

The simulator also indicates that the model can be modified to work well with the introduction of a predator. Adding the predator resulted in a considerably more complex model, requiring several modifications. An additional rule was added, to account for the sheep's reaction to the predator. In addition to this, the rules are weighted differently when the predator is present, simulating fear. With these modifications, similarities could be found between the simulated sheep and real sheep when a predator is present.

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[13] King AJ, Wilson AM, et al. Selfish-herd behaviour of sheep under threat. Current Biology 22. 2012;14:562. Figure 1, Flocking response of sheep to a herding dog.

[14] Grandin T, Deesing MJ. Genetics and Behavior during Handling, Restraint, and Herding; 1998. Figure 4.2, Collective flight zone of a large flock of sheep. As the people walk through, the sheep move away and circle around them. Accessed: 2013-01-28. http://www.grandin.com/references/cattle.during.handling.html.