The effects of interaction with the ground on a flock of starlings

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Abstract

Due to the limited amount of empirical data on flocking in Starlings (*Sturnus Vulgaris*), models are used in order to give insights into the reasoning as to why the flocks behave as they do. Currently a model called StarDisplay factors in the actual flock as well as the borders of their roost for their behaviour. In this research project, the effects of ground avoidance behaviour on flock dynamics have been assessed, using different functions for interaction and by controlling the the amount of the flock that uses the avoidance of the ground functions. This resulted in variances in the shape and volume of the flock.

Using ground avoidance functions resulted in flatter, wider and more compact flocks compared to having no ground interaction. The flock shape also showed similarities to actual flocks behaviour while flying calmly. The volume of the flocks was significantly smaller in most cases, especially when the birds were experiencing more ground interaction.

When the flock had a larger urge to fly lower, the flock became flatter and had a decreased volume. This is due to birds that are flying at the bottom of the flock, they are pushing the birds above them upwards and eventually to the side once they reach an altitude with little to no ground interaction.

1 Introduction

Flocks of birds have increasingly become an issue at airfields due to their hindrance to aircrafts that are landing or taking off (Dolbeer, R.A., Wright, S., Weller, J.R., Begier, M.J., 2011). The birds don't react enough to the aircrafts, causing the birds to crash into aircrafts, which can then cause technical failures or obstruct the view of the pilots. These problems can even have deadly consequences. Knowing that the amount of air travel is only increasing and aircrafts are becoming even quieter due to technical developments, this issue will most likely only increase.

The flocks which are hindering aircrafts are flying at a lower altitude, which means that the ground is also a factor in the behaviour and shape of the flock. This is a subject in which there has been no research yet however.

1.1 Aviation and airfields

Some airfields already deploy methods to try and repel the flocks, such as exterminating entire flocks or employing falconers to use their falcons to scare away the flocks. However these methods are insufficient due to the fact that the flock gets used to falcons and adapt. Employing falconers is also expensive, due to falconers being required to be present to handle to falcons, which also have to be trained (Kitowski, I. et al., 2011).The method of using falconers is not a bad method, but what is important is knowing how and where to most effectively deploy them. This can be achieved through trial and error, but a more efficient method is to build a representative model of the behaviour of the birds and the predators and simulate the airfield in that model.

The behavior of the birds can be modelled for different airfields, but the optimal positions of predator placement have to be redone for every airfield through trial and error. Testing a model is still a lot less expensive and more efficient compared to testing in real life. To have a good representative model a few things have to be included, namely the behaviour of the predators and more importantly the behaviour of the flock. A model called StarDisplay already has behaviour of birds simulated, with the flock only looking at a few other individuals in the flock (Hildenbrandt, H., Carere, C. & Hemelrijk, C.K. 2010). It also has boundary effects, meaning the birds don't want to fly away too far from a certain central point, but still misses interaction of a flock with the ground.

The fact that the model misses the interaction of the starling flocks with the ground means it's not effective to be used as a model to prevent aviation incidents with birds. The problem at airfields is mainly with aircrafts that are landing or taking off, this means the flocks will be flying at a low altitude of somewhere below 500 feet(133 meter). The question is what happens to the volume and shape of the flock when they fly at a low altitude when they have interaction with the ground versus a flock that flies at the same altitude but without that interaction. Some YouTube footage of murmerations as well as research suggest that the flocks are flatter and more spread out when they fly at a lower altitude(Ballerini, M. et al. 2008b).

Aviation incidents with birds is something that has also been the subject of some studies, be it through assessing the actual damages both financially and in human lives(Dale, L.A., 2009), or by studying the reports of wildlife accidents(DeVault, T.L., Belant, J.L., Blackwell, B.F. & Seamans, T.W. 2011). Other types of research include the testing various methods for the repelling of the flocks and judging their effectiveness (Belant, J.L., Martin J.A. 2011; Kitowski, I. et al. 2011).

1.2 Ground avoidance

A very interesting find was that the flock's behaviour could be reproduced in the model using the basic rules of coordination, which are based on separation, attraction and alignment, and adding starling-specific rules. They have simplified aerodynamics for flying, including rolling into a turn (Hildenbrandt, H., Carere, C. & Hemelrijk, C. K., 2010). Secondly they keep flying in the vicinity of their roosting area and finally the starlings in the flock only look at about six or seven neighbours on which they base their decisions (Hemelrijk, C. K. & Hildenbrandt, H., 2012; Ballerini et al,2008).

Attraction entails that the birds are attracted to their neighbours which are far away. Alignment means that the birds change their direction to be the same as neighbours which are less far away and separation entails that the birds are repulsed by nearby neighbours. The rules are made to function on a local level, and through self-organization the flocking behaviour is reproduced.

The model which will be used is StarDisplay, which is a model used in Groningen to try and accurately model flocking behaviour (Hildenbrandt, H., Carere, C. & Hemelrijk, C. K., 2010). StarDisplay mainly models Starling behaviour, and empirical data is supplied from Rome, where there are two places where starling flocks currently are being researched. StarDisplay uses interaction within the flock and the fact that the flock wants to stay above their roosting area as factors for their behaviour.

Interaction with a barrier is something that has been researched earlier. This was done with schools of fish interacting with a wall. Schools of fish use different rules in order to form a school, they don't maintain the same speed when turning (Hemelrijk, C. K., Hildenbrandt, H., Reinders, J., Stamhuis, E, 2010). So what is relevant for the fish schools to use as obstacle avoidance might not be relevant for starling flocks (Hemelrijk, C. K. & Hildenbrandt, H, 2012; Gautrais et al, 2008). In one of these studies it was found that the fish at first align themselves with the wall, but will experience repulsion once it gets too close to the wall, this behaviour is the same for the surface and the bottom of the tank.

In this research project, we attempt to find a function which implements ground interaction in a realistic way. This will be done by seeing if the behaviour matches the behaviour of modelled flocks with what would be expected of real flocks. This can be done by comparing the volume and shape of flocks that are using different functions of ground interaction. This will give an indication of what sort of influence a function will have compared to the other functions. The following questions will be assessed: "What is the influence of the interaction of the starling flock with the ground on the shape of the flock?", as well as: "What is the influence of the interaction of the starling flock with the ground on the volume of the flock?".

The research will include testing a variety of methods and seeing which most closely resembles the actual footage of the birds. This will hopefully give a realistic method of ground interaction that can be applied to the StarDisplay model.

2 Methods

The goal of the research is to test various strategies of interaction of the flock with the ground and compare those to the model with no ground interaction, but also between relevant methods. Since the birds use a small force called 'preferred altitude' which keeps them around a certain altitude, that value will also be varied in order to control the amount of the flock that will use avoidance of the ground function. Two different parameter settings will be used for the preferred altitude. One altitude that will force most of the flock to use a function to avoid the ground and one that should put around half the flock in the avoidance of the ground function.

What will be looked at is the shape and volume of the flock when under the influence of the different functions. These functions are the linear, step and having no interaction function, and are based on earlier mentioned literature (Inada, Y., Kawachi, K(2001)). The shape is looked at both visually as well as by altitude and ratios of the PCA bounding box. The volume of a flock is calculated through two different methods, by calculating the voxel volume as well as the volume of the PCA bounding box.

Furthermore the average altitude of flocks and the absolute amount of birds using the ground avoidance functions are measured over a period of time. The quartiles of the flock are also looked at, to give an impression of how flat a flock is.

Once a model starts it gets 1 minute as the transition period, which is measured real time. This 1 minute allows the flock to adjust to the start setup of the model. Afterwards the data are collected for another 2 minutes. This process is then repeated for another 20 times in order to get representative results.

2.1 Model

The behaviour of the birds are based on the earlier mentioned three rules of attraction, alignment and repulsion. Since the birds are based on real birds, the model also uses basic fixed wing aerodynamics so the birds experience lift, drag and gravity. Furthermore do the birds in the model roll in the turn and don't lose speed when turning. For a more extensive explanation of the model please see the original article (Hildenbrandt, H., Carere, C. & Hemelrijk, C. K., 2010).

2.2 Preferred altitude

An important factor for our experiment which is used in the model is the preferred altitude, which is not only the starting altitude of the flock but also the altitude that a bird prefers to fly at. However this is a small force of a maximum of 0.5% per parameter, which are the horizontal and vertical directions of a bird and the vertical direction of the flock (Hildenbrandt, H., Carere, C. & Hemelrijk, C. K., 2010). This is an important factor because it dictates how strongly a bird wants to fly into the area where there is a avoidance of the ground function active.

2.3 Ground avoidance functions

The comparison will be made between three functions: firstly having a linear connection between priority of avoidance of the ground versus the flock, which is based on the altitude, secondly a fixed altitude from which the avoidance of the ground function works, with no prioritization of the ground versus the flock dependent on altitude, and finally a function where there is no interaction.

2.3.1 Linear function

The linear function for ground avoidance uses two borders, called the upper border and lower border, between which the priority switches. From the upper border upwards, there is no ground interaction and the birds are paying his attention completely on the flock, while from the lower border downwards, the attention of the bird is completely on ground avoidance. Between the upper and lower border, the attention shifts linearly, so 50% between the upper and lower border the attention is directed for 50% to the flock and 50% to avoidance of the ground. As the distance to the ground gets smaller, the flock gets less important and the ground avoidance function becomes more important. The method is taken partly from a research in 2001, where the fish respond more to a predator as it gets closer(Inada, Y., Kawachi, K(2001).

The function is as follows:

$$a = \begin{cases} 0 & : h >= b_u \\ \frac{h-b_l}{(b_u-b_l)} & : b_u < h > b_l \\ 1 & : h <= b_l \end{cases} \tag{1}$$

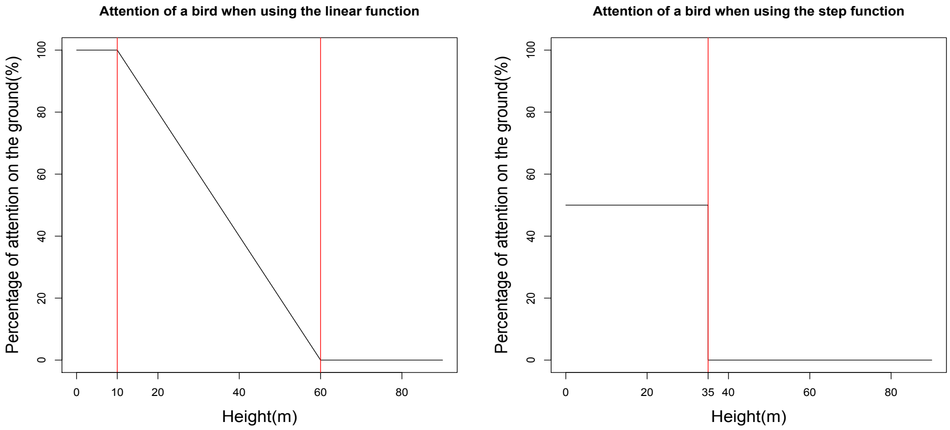
In the above formula a is attention, h is the height, b_l is the lower border, which for the experiment is set at 10 meter, and b_h is the upper border, set at 60 meter . Attention is scaled to be between zero and one and means the extent to which a bird will depend his vertical direction on the six to seven neighbours he's watching compared to avoiding the ground. The focussing then follows the following formula:

$$f_{self} = a * L_{max}$$
$$f_{flock} = (1 - a) * f_{flock}$$

L_{max} is the maximum lift of a starling, f_{self} is the bird his own direction, which is a force away from the ground, f_{flock} is the average direction of the neighbours that a bird has. Visually the formula is shown in figure 1a.

2.3.2 Step function

The step function uses a middle border, which is halfway between the upper and x. Once the bird reaches that altitude, it will split his focus for 50% to the flock and 50% to avoidance of the ground. There is no prioritization dependent on altitude, so getting closer to the ground does not mean the ground avoidance becomes more important. If the bird flies above



(a) (b)

Figure 1: The difference in attention shift for both functions. The red lines depict the borders from which the functions start working.

the middle border then it has no ground avoidance.

The formula is as follows:

$$\begin{aligned} f_{self} &= 0.5 * L_{max} \\ f_{flock} &= 0.5 * f_{flock} \end{aligned} \tag{2}$$

L_{max} is the maximum lift of a starling, f_{self} is the bird his own direction, which is a force away from the ground, f_{flock} is the average direction of the neighbours that a bird has. If an bird gets to an altitude above zero but lower or equal to the middle border then it will shift his focus from entirely on the flock to 50% on the flock and 50% on the ground avoidance.

Figure 1b depicts a visual representation of the function. So the bird focuses entirely on the flock when it is flying above the border below which there is ground interaction, but as soon as it flies below the border it will focus half of his attention on the flock and half on avoiding the ground. The altitude below the bird then flies at below the border is irrelevant.

2.3.3 No avoidance function

Lastly there is the no ground avoidance function. This means that the birds doesn't use any avoidance of the ground functions. This is used to compare the effects of the first two functions to.

2.4 Measurements

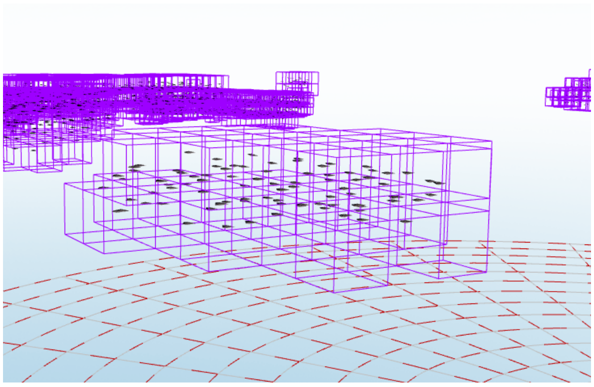


Figure 2: The voxel volume

Of each flock, the number of birds of that flock are measured, along with the voxel volume and the PCA bounding box volume. The voxel volume of the flock is the sum of the volume of the small cubes around the birds. Figure 2 is an example of a flock with the voxel volume visualized. The PCA bounding box is a rectangle placed around the entire flock. Figure 3 is an example of a

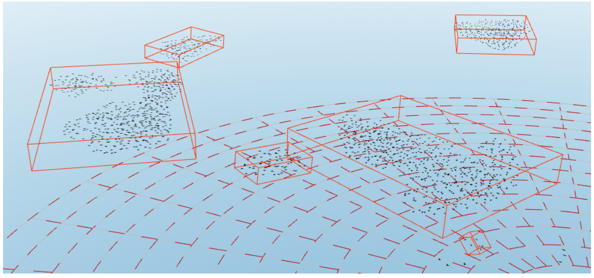


Figure 3: The PCA bounding box

flock with the PCA bounding box visualized. The differences between the volume and value of the PCA bounding box gives information about the shape. If the value of the PCA bounding box is a lot higher than the volume, then that means the flock is irregularly shaped.

Flock
Flock size($\# \ of \ birds$)
Voxel volume(m^3)
PCA bounding box volume(m^3)
The sides of the PCA bounding box($I1(m), I2(m), I3(m)$)
Histogram of the altitude($birds \ per \ meter$)
Using avoidance of the ground($birds \ per \ flock$)

Table 2: The data that are being measured

For a flock, a histogram of the altitude of the birds is also acquired. This measurement shows a bit about the distribution of the flock, altitude-wise, and the lowest and highest flying birds from the flock. compared to some amateur-captured footage.

Finally snapshots are also made at certain times to show shapes of flocks, which can be compared to non empirical, amateur footage of real-life starling swarms to get an idea of their thickness.

2.5 The experiment

The variables of the experiment are kept the same between all three methods, in order to get results which can be compared. The number of birds in the model is kept constant at 5000. The birds do have a preferred altitude, which is a weak force that guides the birds to a certain altitude that they want to fly at.

The function, border and preferred altitude are varied. In table 1 one can see the different parameters which are tested. The method has the following naming: First the ground avoidance function which is used, this can be Lin, the linear function, Step, the step function, or NoInter, the no interaction function. The preferred altitude called Prf, followed by the altitude of the border below which there is ground interaction, which is called Up. The last two values are in meters.

The middle border is calculated with the following formula:

$$b_m = \frac{b_u + b_l}{2} \tag{3}$$

The birds begin the model at the preferred altitude and at before measuring they get a minute as the transition period. The boundary radius was set to 10000 meters in order to prevent birds from reaching the boundary radius and turn. Per experiment, the information in table 2 was acquired over a period from 1 until 3 minutes of run time of the model, in which a snapshot of the flock was taken every 10 seconds, 12 snapshots per run total. This process is repeated twenty times for each method in table 1.

2.6 Analysis

2.6.1 Flock volume

The flock volume is acquired through two different parameters, using the volume of the PCA bounding box, which is visualized at figure 3 and the volume of the Voxel volume, which is visualized in figure 2.

Comparing those volumes says something about how accurately the volume of the flock is measured. If the values of the PCA bounding box are a lot larger than the values of the voxel volume, then the flock has very complex shape. These measurements are used to compare differences between methods via a Wilcoxon Rank Sum test or Kruskal-Wallis Rank Sum test between all of the methods. The

Method	Function	Upper border (m)	Preferred altitude (m)
NoIntrPrf60	No avoidance	60	60
LinPrf60Up60	Linear	60	35
LinPrf35Up60	Linear	60	60
StepPrf35Up35	Step	35	35
StepPrf17.5Up35	Step	35	17.5

Table 1: The experiments were conducted and three different avoidance of the ground functions and two different preferred flying altitude settings per function. The preferred altitude is irrelevant for NoIntrPrf60, since there is no interaction with the ground. The linear function uses a lower border of 10 meters.

voxel volume gives the most accurate representation of the volume of the flock, since the boxes measured are a lot smaller than the PCA bounding box, which can be seen in figure 3.

2.6.2 Flock shape

The shape can be seen visually but also looked at by comparing the altitudes of the birds in a flock and the distribution of the altitudes of the birds in a flock. The altitudes of a flock can be presented in multiple ways, through a histogram, boxplots or plotting the variances of the altitudes of the birds in a flock..

For each simulation, the altitude at which a bird is flying is measured. The altitudes of all the birds in a flock are then combined into a histogram. These measurements will provide information regarding the overall flatness of the flock, as well as the distribution of the flock. The quartiles of those histograms tell something about the shape of the flock as well, how flat they are and what the density of the flock is. If there is a larger difference between the first quartile and the mean than the mean and the third quartile, then that means that the flock is denser above the mean.

These quartiles and median can be used to compare between the different methods using boxplots or again the Wilcoxon Rank Sum test or Kruskal-Wallis Rank Sum test. Also the shortest/medium/longest axis of the flock can be compared in order to get an idea of the height, width and length of the flock. These values are also used to calculate the volume of the PCA bounding box.

Method	Subflocks(in flocks)	Flocks above 4500 birds(in flocks)
NoIntrPrf60	457	229
LinPrf60Up60	281	208
LinPrf35Up60	384	178
StepPrf35Up35	3589	90
StepPrf17.5Up35	547	204

Table 3: The table shows the total amount of subflocks with a minimum of 10 birds per method for all of the runs, as well as the total amount of flocks per method containing more than 4500 birds.

The side of the flock can also be compared to amateur footage from YouTube in order to get an idea of the expected density and spread of a flock.

3 Results

3.1 Subflocks

NoIntrPrf60 in figure 3 depicts the normal scenario when there is no ground interaction. A method with a clear difference from the rest in table 3 is the StepPrf35Up35 method, which is a Step function with a preferred altitude of 35 meter. It had 3150 subflocks over 20 runs with 12 snapshots per run. The average size of a flock with that method was 375 Starlings.

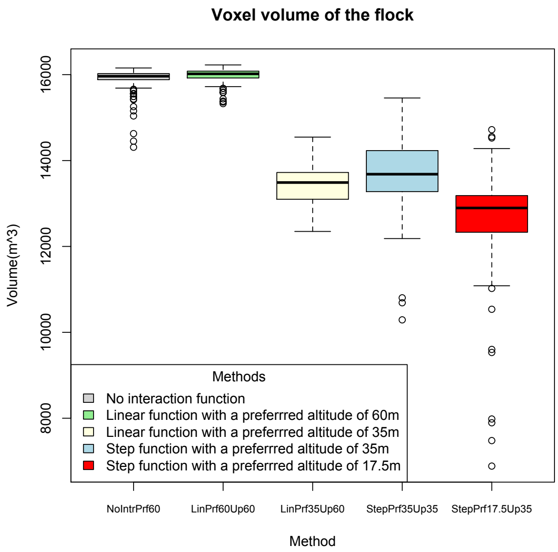


Figure 4: The voxel volumes of the flocks for different methods

The reason the StepPrf35Up35 method for table 3 has such low amounts of large flocks could be due to the flocks being quite flat, which means that the 6-7 neighbours they're paying attention to are horizontal to them instead of below or above them. The connection with neighbours is then easier to lose which means the flocks is easier to break up.

3.2 Volume

The values of the PCA bounding box were quite different from the values of the voxel volume. The voxel volume measurements give the most accurate representation of the volume of the flock, seeing as they are several times smaller than the values of the PCA bounding box. The values of the PCA bounding box are therefore omitted, due to providing inaccurate results. The plot can still be found in appendix 5.1.

Looking at the voxel volumes in figure 4, one can see that the values still differ quite a bit between methods. LinPrf60Up60 and NoIntrPrf60 seem to match closely, however a Wilcoxon rank sum test denies this ($p < 0.001$). The other three methods differ drastically when tested by a Kruskal-Wallis rank sum test($p < 0.001$). Also when testing for a significant difference within the methods, so comparing LinPrf60Up60 to LinPrf35Up60 and StepPrf35Up35 to StepPrf17.5Up35 showed significant differences($p < 0.001$). Comparing LinPrf60Up60 to StepPrf35Up35 and LinPrf35Up60 to StepPrf17.5Up35 also showed significant differences($p < 0.001$).

In figure 4 for the volume when using the same function but a different preferred altitude, the volume is again significantly smaller when the preferred altitude is lower.

3.3 Thickness of the flock

3.3.1 Distribution of the altitude

The altitude at which the birds are flying have been displayed in figure 5. Figure 5a depicts the distribution of the altitude of a model with no avoidance of the ground, which shows a normal distribution of the altitude. Figures 5b and 5d, where the preferred altitude is equal to the altitude at which avoidance of the ground functions start working, show to be skewed to the right. At the altitudes above the border at which avoidance of the grounds functions start working the altitude distribution appears to follow the same pattern as figure 5a. Figures 5c and 5e, show the distribution to be more compact to three altitude values per figure. They are also not normally distributed, according to a Shapiro-Wilk test($p < 0.001$ for both frequency tables).

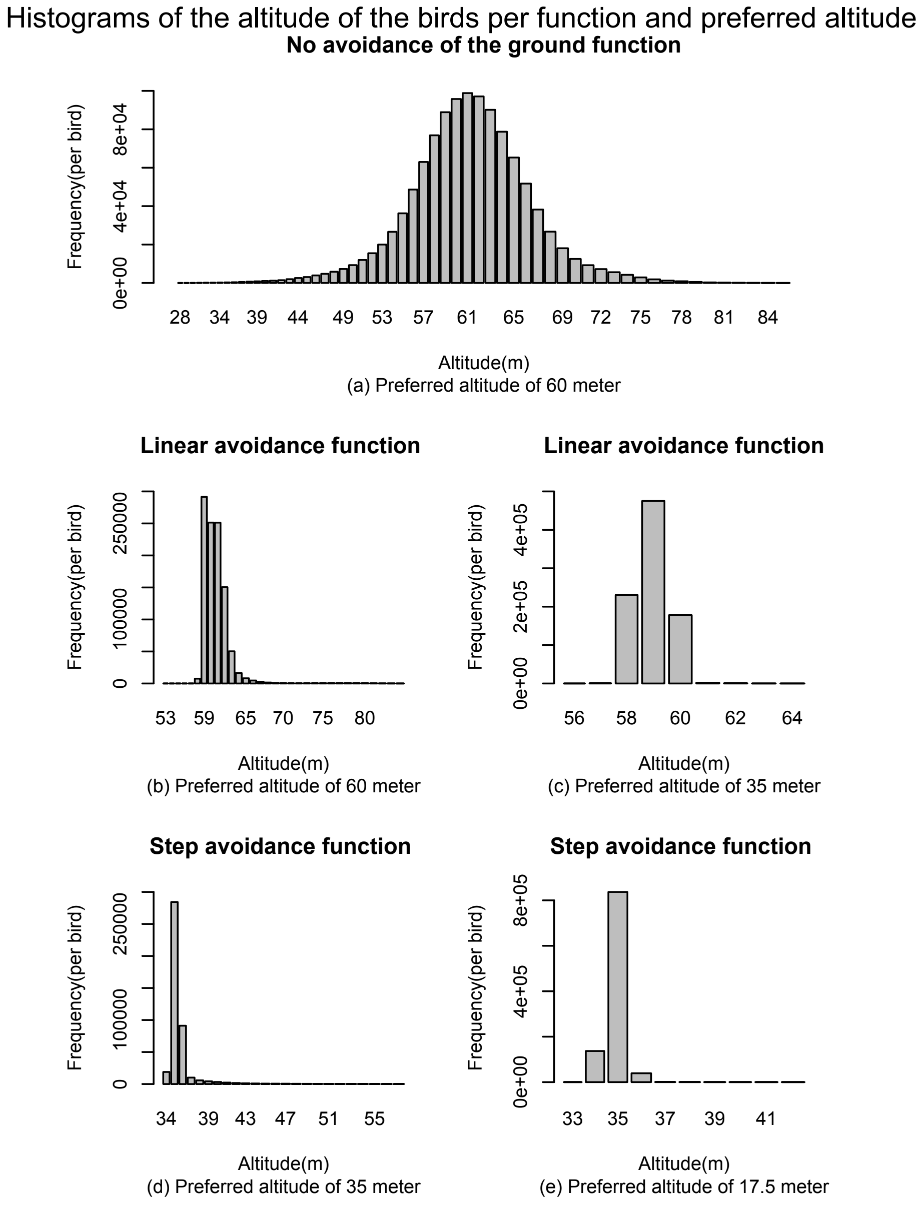
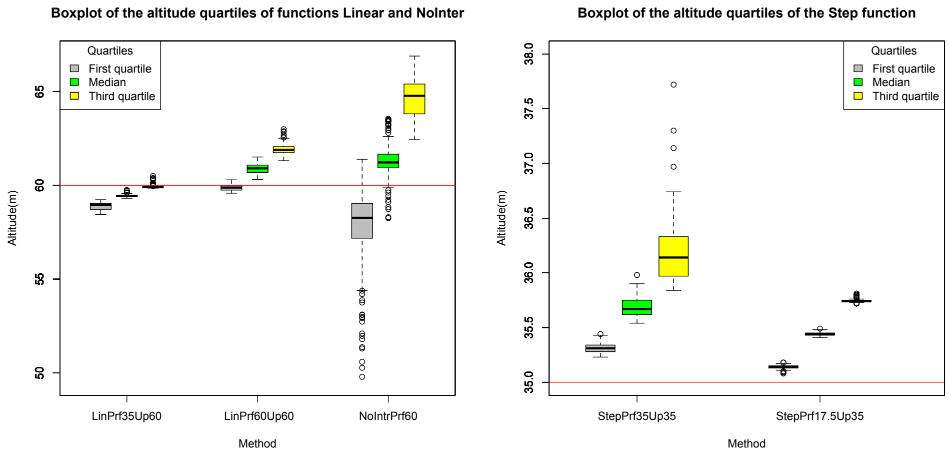


Figure 5: Histograms of the spread of the altitudes per method. Figure (a) depicts the spread when there is no ground avoidance. Figures (b) and (c) show the linear function and figure (d) and (e) show the step function. Figures (b) and (d) are for flocks whose preferred altitude is equal to the border below which there is ground interaction, and figures (c) and (e) are for flocks whose preferred altitude is below the border which there is ground interaction.



(a) (b)

Figure 6: (a) and (b) show the spread of the flock by showing boxplots of the first, second and third quartile. The red line is the border at which avoidance of the ground functions start working.

3.3.2 Median and variance of the altitude

Figure 6a as well as figure 6b show that for all the functions except the linear function with a preferred altitude of 35 meter the median of the altitudes of the flock is above the border below which there is ground interaction. Furthermore, the distance of the quartiles to the median is visibly smaller for the methods with avoidance of the ground compared to the method with no interaction, meaning flocks using avoidance of the ground methods are flatter than the method with no interaction.

This effect can also be seen in figure 7: the variance of the altitudes of the methods with ground interaction versus the one without ground interaction is a lot smaller. The variance of different preferred altitudes but with the same avoidance of the ground method are also different, with the lower preferred altitude methods showing the smallest variance. A Wilcoxon rank sum test confirms a significant differences of the variances within the methods. Comparing LinPrf60Up60 to StepPrf35Up35 as well as LinPrf35Up60 to StepPrf17.5Up35 also shows a significant differences using a Wilcoxon rank sum test.

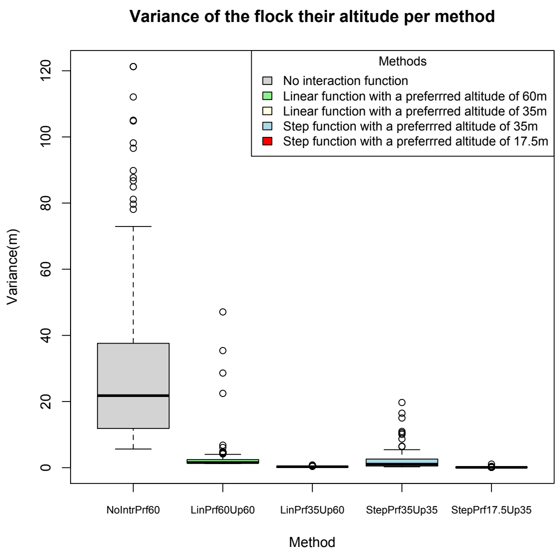


Figure 7: Variance of the altitude of the flocks per method.

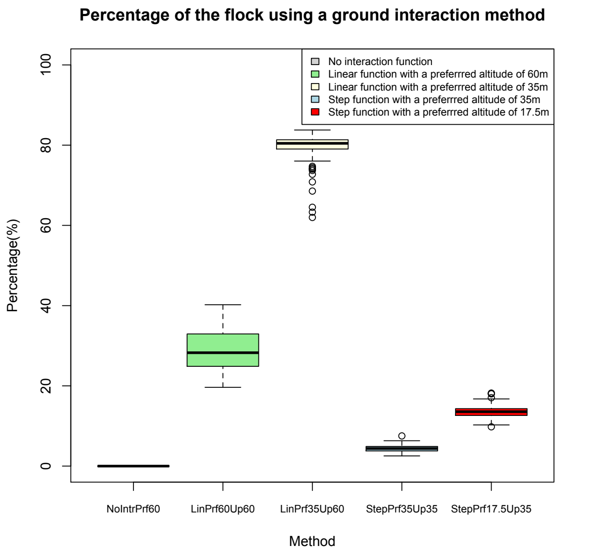


Figure 8: Depicts the percentage of birds in a flock using ground avoidance functions per method.

3.3.3 Ground interaction

Figure 8 depicts the average percentage of the flock that is using the ground avoidance functions. As can be seen, this differs quite a lot per method, with the linear function with a preferred altitude of 35 meter having the highest percentage of ground interaction and the step function with a preferred altitude of 35 meter having the smallest percentage of ground interaction. This is in accordance with what should be expected from figure 6, where LinPrf35Up60 is the only method with a median under the ground interaction border. StepPrf35Up35's first median in figure 6a is highest above the ground interaction border, which is in accordance with a small percentage of ground interaction.

3.4 Thickness of the flock visualized

Table 4 also shows the flatness of the flock for different methods. I_2, I_3 and I_1 depict the width, length and height of the flock respectively in meters. Multiplying these values with each other gives the value of the PCA bounding box. The aspect ratio's in table 4 show the corrected values

				Aspect ratios	
Method	I_1	I_2	I_3	I_2/I_1	I_3/I_1
NoIntrPrf60	20.5	56.1	100.4	2.7	4.9
LinPrf60Up60	8.1	62.9	178.7	7.8	22.1
LinPrf35Up60	2.6	91.5	173.3	35.7	67.6
StepPrf35Up35	9.1	75.3	183.4	8.2	20.0
StepPrf17.5Up35	2.6	93.5	169.8	36.3	65.9

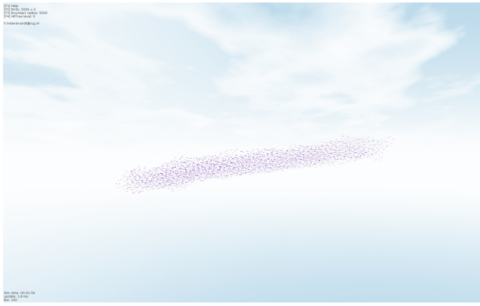
Table 4: The table shows I_1, I_2 ,I_3, which are the shortest/medium/longest axis of the flock, as well as I_2/I_1 and I_3/I_1. These are the aspect ratios of the medium and longest axis corrected for the shortest axis.

of I_2 and I_3 for I_1. The larger these ratios are, the flatter the flock is. For NoIntrPrf60 the aspect ratios are small, and when there is ground interaction involved the values become larger.

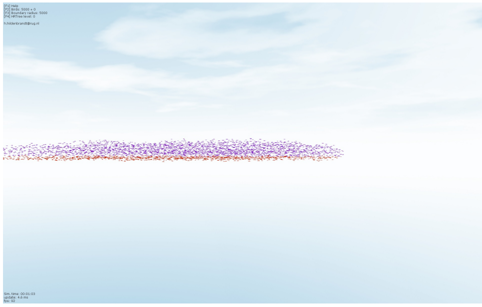
If the preferred altitude is below the border below which there is ground interaction, then the flock becomes a lot flatter, as can be seen with LinPrf35Up60 and StepPrf17.5Up35.

Figure 9 displays images of the model of flocks from the side per method. What can be seen when looking at the flocks in motion is that Step function flocks, which are in figures 9d and 9e, follow a more complex flight path. This flight path isn't shown in the figures. Where 9b and 9c fly in a continuous horizontal path like the actual flocks, the step function birds bounce away from the border below which there is ground interaction and then slowly drift back to it before bouncing upwards again, like a sinusoid.

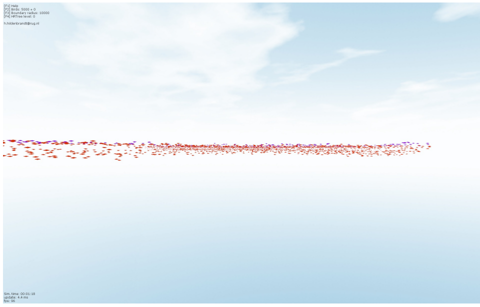
(a) Real flock.



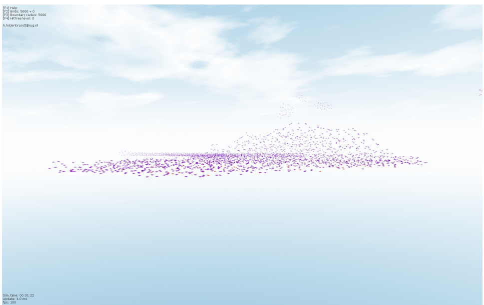
(b) No interaction function with a preferred altitude of 60 meter.



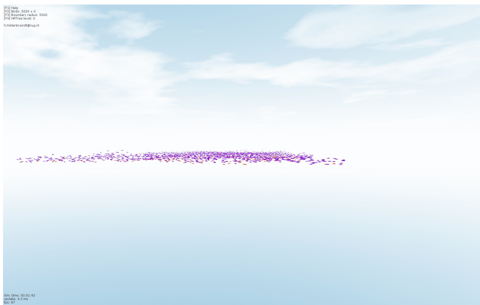
(c) Linear function with a preferred altitude of 60 meter.



(d) Linear function with a preferred altitude of 35 meter.



(e) Step function with a preferred altitude of 35 meter.



(f) Step function with a preferred altitude of 17.5 meters.

Figure 9: (a) displays the shape of an actual flock. (b) displays the shape of a flock when not using any ground interaction functions. (c) and (d) display the shape of the flock when using a linear function with a lower border of 10 meters for a preferred altitude of 60 and 35 meters respectively. (e) and (f) display the shape of a flock when using a step function for a preferred altitude of 35 and 17.5 meters respectively. Birds coloured red are using ground avoidance functions, while birds coloured blue aren't using ground avoidance functions.

4 Discussion

The results show clear differences between the avoidance of the ground functions as well as between the different preferred altitudes within those functions. Comparing the flock to amateur footage also shows some resemblance to the linear function with a preferred altitude of 35 meter. The step function created flocks which didn't resemble actual flocks. However, for this experiment the border below which there is ground interaction was kept at a fixed value of 60 meter above the ground, while having a more flexible border, one that was around 60 but could differ about 5% per bird showed the shape of the flock to be more realistic to an actual flock. It was kept constant for now however in order to minimize possible explanations for the shape and volume of the flock.

4.1 Shape

What can be taken from the figures 4,5, 6a, 6b, is that the shape of the flock changes once the ground becomes a factor. The flock gets flatter, wider and also becomes more compact.

This behaviour can be explained by looking at a flock. The birds at the bottom of the flock typically have the most ground interaction and thus the strongest urgency to fly higher. Birds flying above the border below which there is ground interaction will still have birds below them which are trying to fly upwards. However, the birds above the border are already at the altitude that they want to fly, when the flock his preferred altitude is equal to the border below which there is ground interaction, so instead of going up, they will move to the side. This results in birds who are flying there already to get pushed to the side. Eventually this means that the birds at the border of the flock move to the side as well due to this effect. This creates a flatter and horizontally more spread out flock. For birds using the linear function and where the preferred altitude was below the border below which there was ground interaction, the same happened but the birds on the top of the flock also has a urge to fly downwards.

This effect of the birds flying upwards and pushing other birds to the side is more abrupt for the step function, since the birds seem to overreact to the ground. Instead of the birds flying up slowly and pushing the birds above them away, the lower birds shoot up and force other birds out of the way, since the birds don't want to hit each other due to the separation rule. Figure 9d and 9e show the birds shape from the side for the step functions. Especially for the step function with a preferred altitude of 17.5 meters the flock shows to be just about one bird high.

Table 4 also shows that the I_2/I_1 and I_3/I_1 ratios are a lot larger when the preferred altitude is below the border below which there is ground interaction. This shows the flocks are a lot flatter than the methods where the preferred altitude is equal to the border below which there is ground interaction.

4.2 Volume

Figure 4 depicts the volume of flocks per different method. The LinPrf60Up60 method has volume which appears to be near equal to NoIntrPrf60, but as the Wilcoxon rank sum test showed, they differ significantly. The volume of LinPrf60Up60 is higher than NoIntrPrf60. The reason LinPrf60Up60 and NoIntrPrf60 are so close to each other in volume is due to the influence of the ground being less of a factor for LinPrf60Up60, since the birds want to fly at the altitude of the upper border. So the shape and also volume of the flock more closely resembles NoIntrPrf60, as can be seen when comparing figures 9a and 9b.

The other methods all have significantly lower volumes when compared to NoIntrPrf60, so when the ground has a bigger influence, the volume does decrease. This is logical because as can be seen in figures 9b, 9c, 9d and 9e, the flocks which are using ground avoidance functions are more compressed when compared to the flock without ground avoidance, in figure 9a. Also comparing the within the step or linear functions one can see that when the birds prefer to fly at a lower altitude, then their volume decreases.

4.3 Linear versus the step function

Biologically speaking it is more logical for the birds to prioritise the ground once it gets close and thus more of an issue. Looking at the functions from that perspective it becomes clear that the step function is not the most realistic function. The birds kept flying like a sinusoid, hitting the point where ground interaction becomes a factor and then kept bouncing upwards. This is very different from the amateur footage, which showed the flock mostly flying in straight lines.

The linear function also shows the same behaviour as actual flocks, albeit far from perfect. Figure 9c shows the flock to still be flatter than figure 9a. The birds do keep flying mostly in a straight line, however the density and shape of the flock still is quite different. Since the birds mostly fly near the upper border, making that border more flexible should increase the realism of the flocking behaviour. This is also more logical in real life since it is unlikely that birds have a standard altitude from which they start factoring in the ground for their direction. There is probably some variation when birds start treating the ground as a factor, this also depends on the priorities of the birds.

Something that could also be tested as part of the research, was giving different birds in a flock different functions to use for ground interaction. However, this questions the credibility of the model, seeing as the birds are all of the same species and therefore expected to show the same kind of behaviour. Differing in something fundamental like ground interaction would therefore seem unrealistic.

4.4 Altitudes

As mentioned before, a more flexible border could have a more positive effect on the shape of the flock in getting at least the shape to resemble actual bird flocks.

Another point of interest was that the model started at the preferred altitude. In the model this made sense because of birds having no outside influences other than the flock. However, once the altitude becomes a factor for the behaviour of a bird, then the starting point also becomes more important. In the model the flock was given a minute as a transition period in order to stabilize once they started from their preferred altitude. The preferred altitude of real birds is probably more flexible than in the model, because priorities change due to insects or roosting, instead of starting at an altitude at the middle or top of the ground interaction range.

4.5 Further research

The behaviour that was attempted to be reproduced was the interaction of the flock with the ground. The goal is to create a flock which flies realistically at a lower altitude. As mentioned earlier, by making the border below which there is ground interaction more flexible might create a more realistic flock. The figures of figure 9 show the bottom of the flock to be absolutely flat, which isn't realistic when compared to figure 9a.

Using falconers was shown to be an expensive but useful method, the basics of that idea is to introduce a predator in order to scare flocks. Creating realistic behaviour for the predators as well as the response of flocks to those predators in the model is very important. It'll allow to more effectively test the effects of using falconers at airports, as well as positioning them most efficiently.

The behaviour of flocks in this research was of flocks which seemed to be flying rather peacefully. However, real flocks also showed quite energetic behaviour, in which part of flocks or even entire flocks drop from the sky seemingly at random, after which they can again climb rapidly. The altitude of real flocks in those situations is a lot more dynamic then than it was during calm flight.

There could be two possible explanations for this kind of behaviour. First of all the behaviour could be due to predators. When a predator attacks the flock, the birds try to escape. This behaviour could bring them closer to the ground, meaning there is more ground interaction and thus make the avoidance of the ground response stronger. However, the birds, as well as the predator, also prefer to not hit the ground, which means that the flock's altitude should be more erratic due to the balance between avoiding the ground as well as the predator.

Secondly the energetic behaviour with large altitude differences of the flock could be due to birds landing. The model has shown that flocking behaviour can be achieved with a bird paying attention to only six to seven neighbours. This means that when one or a few of those birds want to land, the overall direction of the small group changes and might influence the neighbours into going along with the original landing bird. However, since the neighbours do not want to land they would then have a stronger avoidance of the ground reaction, seeing as they are just following their neighbour. This could lead to the birds shooting upwards again.

Some preliminary testing of this idea was done by simply giving every bird a very small chance per time step to decide they would want to land. This meant that the bird would ignore ground avoidance functions and fly downwards with a fixed force of 1N, until it reached the altitude of zero meter, then the bird would skid above the ground, their behaviour would reset and fly upwards again. The birds, when flying upwards, would adhere to the function they were using at the time for avoidance of the ground.

Unfortunately just this idea was not explanation enough for the behaviour, what generally happened was that the bird that was landing would drag a few birds up to a maximum of seven along towards the ground. The entire flock was over 4500 birds, so just seven isn't enough. A possible solution could be to implement copying behaviour in the birds; allowing them to respond to neighbours by copying their behaviour. This could for instance increase their chances to for instance get away from predators. This might influence more birds to drop with the few birds that are landing and thus still cause the behaviour.

This is also quite relevant for the research at airfields, because it is a very sudden and fast reaction which can confuse or even scare pilots. If these reactions are caused by an external source, it might even be possible that they can be caused by airplanes that are taking off or landing.

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5 Appendix

5.1 PCA Bounding Box

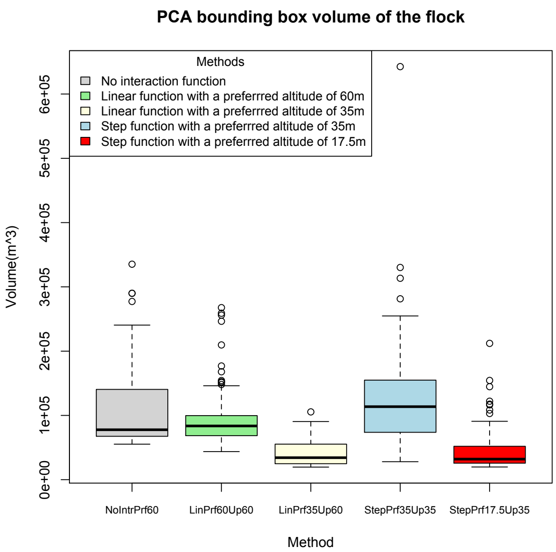

Figure 10: Boxplot of the PCA bounding box volumes.