Simulations on Herding a Flock of Birds Away from an Aircraft using an Unmanned Aerial Vehicle

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Abstract
In this paper, we describe and test a simple algorithm for enabling a single drone to herd a flock of birds away from a dangerous area in which birds may collide with an airplane. To do this, a drone suddenly approaches the flock from beneath, when the flock comes close to the runway. This makes the birds change their path to a higher elevation and safely pass the runway. A simulation platform for evaluating the success of different scenarios regarding this method was created based on Reynolds’ flocking rules. The results showed the possibility of this method to be successful when the drone has a climbing speed suitable for any particular flying speed of birds. In addition to flying speeds, how scattered the birds are in the flock is also another factor that was investigated in the simulations. It turned out that the success of preventing bird strikes may reduce when birds are flying at a far distance from each other.

Introduction
The term “bird strike” refers to any contact between an aircraft and an avian creature or a group of them. For a bird, such an encounter can result in serious injuries or even death and for an aircraft, it may cause damage ranging from a blood smear to significant damage to engines (Hedayati and Sadighi, 2015). These accidents happen while many design features are incorporated in the jet engines to diminish the consequences of bird strikes (Demers, 2009). Bird strikes are a growing problem. With the expanding number of some large flocking birds populations, for example Canada geese (Dolbeer et al., 2014), and also undeniable increase in the number of airplane flights all over the world, it is inevitable that conflict between aviation and birds would happen more and more. Since 2003, the United States and Canada have prohibited high-speed flight at low altitude, because bird strikes are more likely to occur in such situations (Eschenfelder, 2005). According to Federal Aviation Administration (FAA) Wildlife Strike Database, the number of reported accidents per year has been increased from 1,800 in 1990 to 16,000 in 2018. From 1990 to 2014, a total number of 151,267 cases of bird strike had been reported to the FAA. Overall, birds have caused 96.7% of total wildlife strikes to civil aircraft (Dolbeer et al., 2015).

Each airport attracts different reasons which also can vary over species and other parameters such as the time of the year. Several methods have been employed to control the birds and reduce the risk of bird strikes at airports. The basis of one of the most successful controlling programs, habitat modification, is making the airport less attractive to the birds (Harris and Davis, 1998). This is usually done by chemical, auditory, visual and other scaring repellents as well as physical stimuli to disperse birds. Reducing the overall population of birds and habitat manipulation is also another technique used to control bird strikes at airports (Burger, 1983). For instance, in the Frankfurt airport, birds are kept under surveillance with three watch towers equipped with stereoscopic infrared thermal imaging cameras. This can provide an early warning under all weather conditions (Münzberg et al., 2011). In Zagreb airport, trained birds of prey chase the birds as a clearing method to herd them away from the airport (Kužir and Mužinić, 1999).

Figure 1: An aircraft during the landing, facing a flock of birds flying over the runway. This may result in a bird strike (Münzberg et al., 2011).

The idea of using avian predators to clear airports from other birds was first introduced in 1947-49. It has turned out that the most suitable species for that purpose was Peregrine Falcon (Falco peregrinus) (Kužir and Mužinić, 1999), a kind...
of bird that can reach the speeds of up to 240 km/h in normal strikes (Ratcliffe, 1980). However, this falcon is on the list of the world’s endangered species which can limit their future applications for this task. Also, training and controlling such real birds seems to be a difficult job. To address these problems, a remotely piloted robotic Peregrine Falcon called “RoBird” with flapping wings has been recently built and used for herding flocks (RoBird, 2017). The company claims that birds recognize that drone as a true predator and with its consistent operation, fewer birds revert to the area. Furthermore, the usage of normal unmanned aerial vehicles (UAVs) for herding flock of birds flying near airports was under the attention of Paranjape et. al. (Paranjpe et al., 2018). They proposed and tested a novel control strategy enabling a single UAV to safely herd a flock out a danger zone without fragmenting it.

Considering the mentioned problems with using a real Falcon (Kužir and Mužinić, 1999), the limited availability of drones with flapping wings like the RoBird and the complexity of novel control algorithms such as the cases presented by Paranjape et al. (2018) and Pierson and Schwager (2018), we focus on proposing an alternative approach. In this paper, we present and test a simple technique for enabling a commercial drone to be used for preventing bird strikes by herding the flock away. The main concept is that a drone approaches the flock of birds from the bottom and herds them to a higher altitude when radar detects a probable collision of the flock with an incoming aircraft. The scenario will be explained in more detail in the methodology section. One main point of this research is to use simulation software as a test bed for examining the efficiency of the algorithm. To do this, it has been supposed that the birds demonstrate an emergent flocking behavior by obeying the simple rules introduced by Reynolds (1987). As can be found in the work of Vaughan et al. (2000), utilizing a minimal simulation model is a feasible way of investigating the performance of flock control systems prior to transferring them to the real world.

Background

Flocking Behaviors of Birds

The idea of Boids originally presented by Reynolds (1987) was to formulate a parameterized model of the aggregate motion of flocks, herds, and schools so that they demonstrate a complex emergent life-like behavior. This was achieved by defining only three simple rules: “Collision avoidance”, “Velocity matching” and “Flock centering”. In this model, each boid in the group avoids collisions with nearby flockmates, attempts to match velocity with them and tries to stay close to the nearby flockmates only based on its local perception of the world. To make the flocking behavior more realistic, this idea has been extended in many ways. For instance, Hartman and Benes (2006) defined a new rule which generates random changes in the leader of the boids. A boid on the front edge of the flock has a higher chance to be the leader after increasing its velocity and escaping from the others.

In the original paper by Reynolds (1987), environmental obstacle avoidance was also considered using two different methods. One of them uses a force field vector from the object which makes a growing opposing force towards the boid. This concept has some deficiencies. For example, when a boid is flying perpendicularly to an obstacle, the only effect of the force field from the obstacle is to slow down the boid. Although Chiara et al. (2004) have proposed some corrections for tackling these problems, there is a more robust model called steer-to-avoid which is a better simulation of the animal’s natural mechanism (Reynolds, 1987). Using this mechanism, the boid only considers obstacles in the visual field in front of it and changes its way if it is necessary.

The response of flocks and schools to a predator’s attack also has been added to the original boids model. Schooling of fishes protects the members against predators by confusing predators with their collective evasion behaviors. Zheng et al. (2005) added three new components of schooling, cooperative escape, and selfish escape behavior to Reynolds’ model as well as a rule for choosing one of them in proper timing to generate efficient escape behavior. Lee et al. (2006) did analogous work for flocks of birds.

Birds Encountering Aircraft

Bird strike itself is dangerous if it happens. However, the hazards posed by the different species or groups of similar species present in the airport to aviation is not the same for all kinds of birds (Dolbeer et al., 2000). Ten primary risk factors were introduced by Carter (2001) in order to prioritize this threat. These factors include the overall population of the species, mass and surface area of an individual animal, their group size, their distance from runways, the number of reported strikes, and the ability of the species to actively avoid aircraft collisions. About the last-mentioned factor, it should be mentioned that not all the birds are uniformly able to avoid contact with an oncoming airplane. Researchers have examined the injuries on some types of sacrificed birds and found that they must be going up while moving towards the aircraft, dropping while moving away from the aircraft, or banking away while moving horizontally across the aircraft’s path. This means that they utilize anti-predator behaviors when encountering an airplane (Bernhardt et al., 2010). However, some species of birds are unable to stay out of the way of the aircraft flight path all together. Species like storks, curlows, and geese are completely unskilled at maneuvering out of the way of fast planes. It has been found that the Canada and snow geese are the most threatening species for the aircraft and the highest priority should be given to controlling those species in the areas where they are present (Carter, 2001).

Table 1 shows the six most struck group of species according to the FAA National Wildlife Strike Database
Table 1: Top six groups of birds with the largest number of reported strikes by aircraft, according to data from FAA National Wildlife Strike Database, 1/91 – 5/98. For each group, some examples of the flying speed of species are included.

<table>
<thead>
<tr>
<th>Species Group</th>
<th>Strikes Reported</th>
<th>% with Damage</th>
<th>% with Effect on Flight</th>
<th>Example</th>
<th>Flying speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulls</td>
<td>2599</td>
<td>20</td>
<td>18</td>
<td>Larus argentatus (Tucker and Schmidt-Koenig, 1971)</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Larus atricilla (Tucker and Schmidt-Koenig, 1971)</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Rhodostethia rosea (Hedenström, 1998)</td>
<td>13.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Larus sabini (Hedenström, 1998)</td>
<td>13.9</td>
</tr>
<tr>
<td>Blackbirds/Starlings</td>
<td>1052</td>
<td>6</td>
<td>10</td>
<td>Sturnus vulgaris (Linz et al., 2007)</td>
<td>19.4</td>
</tr>
<tr>
<td>Sparrows</td>
<td>622</td>
<td>2</td>
<td>6</td>
<td>Passer domesticus (Schnell and Hellick, 1978)</td>
<td>12.7</td>
</tr>
<tr>
<td>Geese</td>
<td>532</td>
<td>56</td>
<td>32</td>
<td>Branta canadensis (Tucker and Schmidt-Koenig, 1971)</td>
<td>13.9</td>
</tr>
<tr>
<td>Hawks</td>
<td>452</td>
<td>25</td>
<td>21</td>
<td>Falco sparverius (Tucker and Schmidt-Koenig, 1971)</td>
<td>11.1</td>
</tr>
<tr>
<td>Ducks</td>
<td>401</td>
<td>41</td>
<td>23</td>
<td>Anas rubripes (Tucker and Schmidt-Koenig, 1971)</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Anas acuta (Welhun, 1994)</td>
<td>16.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Anas platyrhynchos (Welhun, 1994)</td>
<td>21.6</td>
</tr>
</tbody>
</table>

Methodology

In this work, the proposed and simulated scenario is that a flock of birds is flying over the runway of a small airport in which an aircraft wants to land as well. The flock is assumed to fly on a straight path perpendicular to the runway at a fixed altitude. The scenario is designed in such a way that the radar has detected if the flock remains on its path and keeps its speed, the birds will collide with the landing airplane at a specific area over the runway. We call this area the “collision box”. In other words, it has been calculated based on the speed of the flock that both the flock and the airplane will be at the same place at the same time. To prevent the collision, a UAV approaches the flock from the bottom at the edge of the runway, to herd them to a higher and safe altitude before they reach the runway. To do this, once a potential conflict between the flock and the airplane is detected, the UAV starts flying at an altitude about a few meters above the ground and actively adjusts its position to be in the way of the upcoming flock at the edge of the runway. Then, at a proper moment, the UAV starts to gain elevation with a given climbing speed to meet the flock before they reach the runway.

In this paper, we denote the position of the i-th bird at the time step t in the three-dimensional space as $P(i,t) = (P_x(i,t), P_y(i,t), P_z(i,t))$, or in a shorter form $(P_x, P_y, P_z)$. We also have a velocity vector $(V_x, V_y, V_z)$ for each bird denoted similarly. The position and velocity parameters of the flock $(P_{flock} \text{ and } V_{flock})$ are the position and velocity of the center of mass of the flock, assuming that all boids have a same mass, and can be calculated by

$$P_{flock}(t) = \frac{1}{n} \sum_{i=1}^{n} P(i,t), V_{flock}(t) = \frac{1}{n} \sum_{i=1}^{n} V(i,t),$$

(1)

where $n$ is the total number of birds. The moment when the UAV should start going up can be easily calculated by having its climbing speed $(V_{UAV,y})$ which is sometimes called “ascent speed”, the speed of the upcoming flock $(V_{flock,x})$ and the altitude of the flock $(P_{flock,y})$. The UAV starts when the flock has the distance

$$D_{start} = \frac{P_{flock,y} - V_{UAV,y} V_{flock,x}}{V_{UAV,y}}$$

(2)

to the edge of the runway.

Simulation World

In this study, simulations have been done using Webots R2019b. Webots is a free and open-source robotic simulation software that provides a rapid prototyping environment for modeling, with the ability of programming using various languages and then simulating mobile robots in a virtual and realistic environment (Michel, 2004). Fig. 2 shows the simulation world with components that will be described in the following. The coordinate system that we refer to is also shown in the picture.

To make the simulation world, the total of twenty spherical objects each representing a bird of a flock have been created. At start of each run of the simulation, their positions...
are set randomly within a cubic box. The size of this cube can be adjusted, so we can have the flock initially concentrated in a small volume or spread in a large space. However, the number of boids was constant for all runs.

A rectangular arena with a 30 m width placed on the ground depicts the runway of the airport. The width of the runway was chosen based on the FAA Runway Dimensional Standards for Transport Airports (Airport Approach Category C and D) (Ashford et al., 2011). In order to detect possible collisions between birds and the aircraft, a rectangular box corresponding to the size of the airplane created above the runway. This is the “collision box” as mentioned before. To avoid complexities, it is assumed that a collision will happen if any of the birds enter that box. This occurs with different levels in terms of injuries posed by the flock, as will be explained later. Based on the dimensions of an arbitrary airplane which is an ATR 72-600 in this study, this box is 27.17 m long, 27.05 m wide and 7.65 m tall. These numbers correspond to an ATR 72-600’s overall length, wingspan, and height, respectively.

A built-in prototype for the UAV was also added to the world at the edge of the runway. For the UAV, the only real factor which is important is its ascent speed, or in other words, the vertical speed while it is climbing. This speed varies between 4 m/s for small drones like Parrot ANAFI Thermal to 7 m/s for Yuneec H520, which is a hexacopter for professional use. In the middle of the range, DJI Mavic2 Pro and DJI Phantom 4 Pro V2.0 are examples of widely-used drones with the climbing speeds of 5 m/s and 6 m/s, respectively. In the simulation, those values were considered as \( V_{UAV,y} \).

**Figure 2:** The simulation world and its components including the boids, drone, runway, and collision box. The coordinate system is also shown in the bottom left of the figure. The drone is not visible due to its small relative size.

**Governing Rules**

In the Webots simulation environment, a supervisor node running a script written in C programming language controls all the simulation process. Boids pseudocode explained by Parker (2007) is the basis of this program. This pseudocode is a more clear explanation of the Reynolds boids algorithm with a few extra tweaks and some reasonable values for the constants. Based on the original boids algorithm proposed by Reynolds (1987), there are three rules working independently within each boid based on local information causing the boids to show an emergent flocking behavior. This means that each boid will get moved by each of the three rules giving a velocity vector. These vectors are summed with each boid’s current velocity to form the new velocity as the indicator of how much and in what direction it should move in any time step. A small random number ranging between 0 to 1 m/s will be added to velocity vectors componentwise at each time step, independently for each boid. This models noise caused by the environment such as winds that can randomly affect the bird’s speed.

For this simulation, we also needed two extra behaviors in addition to the flocking behavior of birds: a tendency towards a particular place as a goal (goal-oriented flight) and a tendency away from a particular place as an obstacle (obstacle avoidance). These are kinds of motor-schema behaviors which are inspired by animal actions and are helpful for their navigational tasks (Arkin, 1998). All the behavioral responses can be represented by vectors generated using a potential field approach. Each motor schema contributes an output vector that defines the manner the robot should move in response to the perceived stimuli.

Achieving a goal-oriented flight behavior for the \( i \)-th boid was done by adding a potential field

\[
\tilde{F}_{\text{tend to place}}(i, t) = (P_{\text{goal}} - P(i, t))/C_{\text{goal}}. \tag{3}
\]

This makes a potential field causing a tendency toward a goal at the position of \( P_{\text{goal}} \), with the factor of \( C_{\text{goal}} \), and decreasing linearly while getting closer. In the simulation, the goal was defined in the very far distance at an altitude similar to the flock’s initial elevation to make the flock move perpendicular to the runway on a straight path. In addition, the obstacle avoidance behavior was added to the model in a similar fashion:

if \( || P_{\text{obs}} - P(i, t) || < C_{\text{thr}} \), then

\[
\tilde{F}_{\text{obstacle avoidance}}(i, t) = -(P_{\text{obs}} - P(i, t))/C_{\text{obs}}. \tag{4}
\]

Here, we have a similar potential field but this time away from the obstacle. This behavior will only be activated when a boid becomes closer than a threshold defined as \( C_{\text{thr}} \) to the obstacle. This is based on the assumption that a bird will not perceive the danger of predators and obstacles beyond its sensory range. In our case of study, the UAV acts as an obstacle whose location changes actively within the simulation (\( P_{\text{obs}} = P_{UAV} \)). The potential field for goal-oriented flight and obstacle avoidance behavior has internal parameters \( C_{\text{goal}} \), \( C_{\text{thr}} \), and \( C_{\text{obs}} \) that produce adjustability in their implementation and could be adapted to model different bird species’ characteristics.
Finally, an additional function to limit the magnitude of the boids’ velocities was added to the controlling algorithm: if \( \| V(i, t) \| > V_{lim} \), then

\[
V(i, t) = V_{lim} \frac{V(i, t)}{\| V(i, t) \|}.
\] (5)

While the flock has a tendency toward a particular goal, boids will keep going with their maximum possible flying speed \( V_{lim} \) most of the time. This enables us to have different flock speeds \( V_{flock, x} \) by changing the \( V_{lim} \) of the birds.1

**Metrics**

As previously mentioned, the initial position of the birds can be set within a small or a large cubic area. It will be discussed later in the research hypotheses that having the flock more scattered may make the herding process harder than the case having a flock with birds concentrated near one point. To quantify how scattered the birds are, at each time step \( t \), we define a parameter called Dispersal as

\[
D(t) = \frac{1}{n} \sum_{i=1}^{n} \left( |P_x - P_{flock, x}| + |P_y - P_{flock, y}| + |P_z - P_{flock, z}| \right).
\] (6)

With this definition, we have larger values for \( D(t) \) when birds are more distant from the center of the flock \( P_{flock} \).

In addition, we define a scoring parameter which allows us to measure how successful the UAV is in preventing potential bird strikes. The formula below is based on the fact that the most successful herding is when none of the birds enter the collision box. On the other hand, if all the birds arrive at the most dangerous point in the space at the same time, theoretically, the mission of UAV would be a complete failure. Considering the center of the collision box as the most dangerous point, we can define success percentage \( S(t) \) for each time step \( t \) as

\[
e_1(i) = \frac{|P_x(i, t) - P_{box, x}|}{\frac{1}{2}d_{box, x}}, \quad e_2(i) = \frac{|P_y(i, t) - P_{box, y}|}{\frac{1}{2}d_{box, y}}, \quad e_3(i) = \frac{|P_z(i, t) - P_{box, z}|}{\frac{1}{2}d_{box, z}},
\]

\[
S(t) = \frac{1}{n} \sum_{i=1}^{n} \left[ \prod_{j=1}^{3} \max(1 - e_j(i), 0) \right].
\] (7)

Here, \( d_{box} \) refers to the dimensions of the collision box and \( P_{box} \) is the position of its center. \( S(t) \) would be equal to one if all the birds are outside of the box and zero if all are at its center. Over the entire scenario, minimum success percentage, \( \min(S(t)) \), can be considered as a measure for the success of the UAV. This shows the degree of success at the worst moment of the simulation.

**Research Questions and Hypotheses**

Using the simulation platform as described, we performed some tests to answer these two research questions:

1. How do changes in the species of the birds, which results in different flock speeds, impact the success of the UAV in preventing bird strikes?

2. How does the initial dispersal of the flock affect the efficacy of the UAV for the purpose of preventing bird strikes?

To answer the first research question, we investigated scenarios with different bird speeds. We changed \( V_{lim} \) for varying the boids’ velocities. Then, we tested different UAVs having ascending speed \( V_{UAV,y} \) ranging from 4 m/s to 7 m/s. We hypothesize that while encountering a flock of higher-speed birds, the UAV should have a higher climbing rate in order to effectively herd them away from the aircraft landing path. After running this experiment, it will be determined which models of a drone can be used for particular species of bird.

About the second research question, the hypothesis is that when the flock is more scattered, it is more difficult to herd them using only one drone. The effects of variations in the initial flock dispersal of flock \( D(0) \) was studied to answer this. We also considered the consequences of having different \( (C_{thr}, C_{obs}, C_{goal}) \) coefficients on the answer of the research questions.

**Results and Discussion**

**Proof of Concept**

To illustrate how the drone acts for preventing bird strike, Fig. 3 shows the flight path of the flock projected on the X-Y plane in two similar cases with and without a UAV. Without any deterrent obstacle, birds keep on flying to reach their defined goal and they may collide with the airplane when it enters the collision box. In the example shown in Fig. 3, birds’ initial positions are within a \( 10 \times 10 \times 10 \text{ m}^3 \) space, \( C_{thr} = 5 \text{ m}, C_{obs} = 20, C_{goal} = 500, V_{lim} = 12 \text{ m/s}, \) and \( V_{UAV,y} = 5 \text{ m/s} \) (DJI Mavic 2 Pro). It can be seen that when the drone approaches the flock from beneath, the flock shifted their path to a higher altitude. This caused the minimum success percentage to be 99.3% using the UAV, instead of 68.8% without it.

**Effect of Flying Speeds**

To investigate the effects of variations in the speeds of both the UAV and the birds, we ran a total of 60 simulations for...
Figure 3: Flight path of the flock in two scenarios with and without a drone herding it. Without any obstacle, birds continue their path inside the collision box and bird strike happens.

12 different conditions, five times each. These conditions were all the possible combinations of having birds traveling with 10 m/s, 15 m/s and 20 m/s speed approached by drones with 4 m/s, 5 m/s, 6 m/s and 7 m/s climbing rates. The chosen values for the birds’ flying speeds are representative of three examples in the range of actual species typical flying speeds compiled in Table 1, and values for drones’ climbing speed are examples from previously mentioned commercial models. In all the conditions, other factors remained unchanged: birds initial positions were within a 10 × 10 × 10 m³ space located 45m far from the edge of the runway, Cthr = 5 m, Cobs = 20, and Cgoal = 600.

Table 2 summarizes the mean and standard deviation of the minimum success percentage for all the five experiments associated with each condition. It can be seen that when we had a flock of birds with higher flying speed, using a drone that gains elevation too fast was not effective. This means that, for example, when a flock of *Sturnus vulgaris* with the flying speed of near 20 m/s is going to collide with the aircraft, the ascent speed of drone should set to 4 m/s in order to have an acceptable result with a minimum success percentage of 97.81%. According to a t-test, there was no significant difference between using that drone or the one with 5 m/s or 6 m/s climbing speed (p-values = .446164 and .0505 > .05). However, using a drone with 7 m/s instead of 4 m/s vertical speed made a significant difference (p-value = .036663 < .05). When the flock had a lower flying speed of 10 m/s, all the tested drone speeds produced almost the same minimum success percentage ranging from 99.89% to 98.48%. In the middle of the tested range, i.e. 15 m/s flying speed, a drone with at least 5 m/s should be used to have the best efficacy. This improved the minimum success percentage in comparison with using a drone with 6 m/s ascent rate (p-value = .028279 < .05).

Table 2: Minimum success percentage (Average and Standard Deviation) for five times running the simulation with UAV ascent rate and birds flying speed being set to indicated values.

<table>
<thead>
<tr>
<th>Birds flying speed (m/s)</th>
<th>UAV ascent rate (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>99.9(0.06)</td>
</tr>
<tr>
<td>15</td>
<td>99.8(0.18)</td>
</tr>
<tr>
<td>20</td>
<td>97.8(1.34)</td>
</tr>
</tbody>
</table>

For ensuring that all the birds will ‘feel’ the presence of the obstacle (drone) and show a suitable reaction to it. In that case, we saw the lowest minimum success percentage of 93.98% on average.

**Effect of Dispersal**

By setting the initial birds’ positions located within a 7 × 7 × 7 m³ space to a 18 × 18 × 18 m³ space in 30m distance from the runway we achieved different initial dispersal (D(0)) values as defined in Eq. 6. By repeating the experiment five times for each one-meter step increase in the initially allowed space for birds to be present, we came up with a total of 60 pairs of initial dispersal (D(0)) and minimum success percentage (min(S(t))). Here, in all the experiments, other parameters set as follows and remained unchanged: Cthr = 5 m, Cobs = 20, Cgoal = 600, Vlim = 15 m/s, and VUAV,y = 5 m/s (DJI Mavic 2 Pro). Fig 4.(a) shows these points on a scatter plot. The decrease in the success percentage while having larger dispersal values, i.e. wider dispersal, confirms our hypothesis that when the flock is more scattered, it is more difficult to herd them using only one obstacle.

It can be seen in Fig 4.(a) that when the initial dispersal...
was smaller than about 7 m, all the tested herding cases had a minimum success percentage close to 100%. With the dispersal getting larger and birds flying further from the center of the flock, the chance that all the birds being alarmed by the drone decreases. This is clear in Fig 4.(a) as for the dispersal factors larger than about 10 m we saw several unsuccessful cases with a minimum success percentage of below 80%.

Since two parameters of \( C_{th} \) and \( C_{obs} \) define the behavior of birds while avoiding obstacles, we are also interested in investigating the effects of making changes in each of those. To test whether we can enable the UAV to successfully herd flocks with even large dispersal, we first examined the effects of having a larger \( C_{th} \). This will be achieved when the birds sense the drone and act to avoid it from a farther distance. In a real-world scenario, having a larger drone or combining two of them moving in a group, or even making the UAV produce a loud sound may lead to this. Fig 4.(b) shows 60 points of repeating the last experiment with initial birds’ position located within a \( 9 \times 9 \times 9 \) m³ space to a \( 20 \times 20 \times 20 \) m³ space this time with \( C_{th} = 6 \) m instead of \( C_{th} = 5 \) m. All other parameters remained the same. In terms of results, a shift of points to the right in Fig 4,(b) in comparison to Fig 4.(a) was seen. This time, all the herding scenarios with an initial dispersal of less than 10 m were quite successful. Previously, when we had \( C_{th} = 5 \) m, we could expect to have only successful herdings with initial dispersals smaller than 7 m.

The other factor to investigate is \( C_{obs} \). Having smaller \( C_{obs} \) means having a stronger potential field away from the obstacle. This happens when the birds avoid the drone with a higher speed and might be achieved by some stronger stimuli. The effect of having \( C_{obs} = 10 \) while \( C_{th} = 5 \) m is illustrated in Fig 4.(c). Again, 60 points in the figure correspond to initial birds’ position adjustments from a \( 9 \times 9 \times 9 \) m³ space to a \( 20 \times 20 \times 20 \) m³ one. This time, herdings of flocks with an initial dispersal of smaller than 9 m seemed quite successful for all the cases. By looking at these results, it can be concluded that in order to achieve a better efficiency when the flock is scattered, both ways of causing the birds react to the drone from a larger distance or with a higher speed work well. The comparison of cases (b) and (c) shows that the first approach, i.e. increasing the bird’s awareness distance, works even slightly better than the second one.

Goal-Oriented Flight

Up to here, we investigated how changes in speeds \( (V_{UAV,y} \) and \( V_{lim} \)), initial dispersal \( (D(0)) \), and obstacle avoidance parameters \( (C_{obs} \) and \( C_{th} \)) affect the success of this robotic herding. Another factor which has an impact on the behavior of the birds, and thus, can change the results of all conducted experiments is \( C_{goal} \) - this parameter determines how much tendency the birds have toward their goal. Setting a lower

\( C_{goal} \) makes them have a stronger tendency to go straight to their defined goal. In this case, because of a higher magnitude for the potential vector, the noises and obstacles will have less impact on the flying path of birds. To test this, we set \( C_{goal} \) to 300, 600, and 1200 while keeping \( C_{th} = 5 \) m, \( C_{obs} = 20 \), \( V_{lim} = 15 \) m/s, \( V_{UAV,y} = 5 \) m/s, and initial position of the within a \( 6 \times 6 \times 6 \) m³ space 22.5 m far from the runway.

Fig. 5 depicts the trajectory of the birds’ movement projected on the X-Y plane. On one hand, with \( C_{goal} = 300 \), birds strongly tended to their goal and the UAV only could disturb them a little. All of them followed their way inside the collision box and the minimum success percentage fell to 62.1%. On the other hand, \( C_{goal} = 1200 \) made the flock vulnerable to noise, and they continued their way keeping going up slightly even after being herded by the drone. \( C_{goal} = 600 \) turned out empirically to be a reasonable choice and was used for simulations in the two previous sections.

Limitations and Future Work

In this study, we tried to take advantage of an Artificial Life concept, i.e. agent-based emergent flock modeling of boids, to provide a framework to test and simulate a solution for a real-life problem. Practical work on the bird strike problem in a real physical world are not easy tasks to do. We can
Figure 5: Flight path of the birds of the flock having different values as $C_{\text{goal}}$, thus, showing different tendencies toward their goal, decreasing from top to bottom.

not expect a flock of birds to exhibit similar behavior in a reachable area multiple times, so we tested different strategies regarding preventing them from entering a dangerous space in simulation reflecting a range of bird species. In other words, having an entire flock under control for such an experiment is challenging or even impossible. The piece of software developed in this study provides the opportunity to have a flock of birds in a simulated environment and see how changing variables can impact each scenario.

Despite all the mentioned benefits, generalizing the achieved results for use with real birds is itself a challenge. There are some coefficients including $C_{\text{thr}}$, $C_{\text{obs}}$, and $C_{\text{goal}}$ which govern the emergent goal-oriented flight and obstacle avoidance behavior without any clear and tangible logic behind choosing their values. As the results showed, changing each of those variables could change a completely successful scenario to a failure. Additionally, within the original boids rules implemented by Parker (2007), there were three coefficients that remained unchanged as it was mentioned that they were tuned for having a realistic flocking behavior. Empirically, we chose $C_{\text{thr}}$, $C_{\text{obs}}$, and $C_{\text{goal}}$ to generate a seemingly acceptable behavior, but the question is to what extent can we expect a real flock of birds acts like the simulation? To have more accurate results, the parameters of the boids behaviors should be adjusted for specific types of birds. For this application, most of the attention should be directed to Canada geese ($\textit{Branta canadensis}$) which are the most harmful species for aircraft (Carter, 2001).

Although the effects of changing many factors were investigated in this study, these simulations can be done for examining even a wider range of variables. For example, the number of birds in a flock is another variable that can be important for the success of the herding. As previously mentioned, flock size can also affect the flying speed of birds (Hedenström and Akesson, 2017), which makes solving this problem even more complex. Furthermore, with different aircraft, collision boxes can vary by size in the performed experiments. The flight path and the number of drones can be also modified. The effects of varying all these seemingly important variables can be investigated in the future work.

As an extension of this study, another aspect to consider is the model of birds’ collision avoidance strategy. We used vector fields to make the birds move away from the obstacle, i.e. the UAV. This was beneficial because it made the algorithm more simple and easier to understand. However, the steer-to-avoid model presented by Reynolds (1987) or even the more complicated model proposed by Lee et al. (2006) can be also employed.

**Conclusion**

This study aimed to propose a strategy for preventing bird strikes in airports and conduct some experiments about that using a simulation environment. In this scenario, a commercial drone herds a flock of birds by approaching them from the below when they are detected approaching the edge of the runway risking collision with the oncoming aircraft if they were to continue their trajectory. This strategy has the advantage of affording simple control of the UAV and does not require any special infrastructures except a radar for detecting the birds.

Based on the literature, not all birds are the same in terms of being subjected to bird strike accidents. Thus, we focused on the groups with the most reported collision cases and first investigated how differences in the traveling speed of each affect the success of the preventive task. It was found that when the birds have a higher speed, the drone must gain elevation with lower speed to successfully move the flock up. This finding is important especially when we face a flock of starlings or ducks that fly faster than other considered species.

Additionally, we confirmed that when the birds are flying more scattered in the flock, the chance of the herding task being successful reduces. This happens when birds are large in size, like Canada geese, and do not fly so closely to avoid contact between flockmates. We tried changing the parameters of the obstacle avoidance behavior and found that if the birds get alarmed and show a reaction to the drone from a farther distance or avoid it with a higher speed, they will be prevented more successfully from entering the danger zone.

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