

# Project Report: Swarm Behavior and Control

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## I. INTRODUCTION

Aggregations among animal species are very common in nature. These species vary from a school of fish, to a flock of birds, to a herd of sheep, to humans walking in a crowd down a busy city block. Remarkably, these self-organized colonies have no sort of central control, yet are able to work together cohesively only using localized interactions with a simple set of rules to achieve global benefits such as forming certain patterns, moving toward desirable destinations, and avoiding threats.

Investigating and building models that simulate the rules and patterns of these remarkable aggregations are very beneficial to humans, animals, and the environment. For example, research in social insect behavior has made it possible for computer scientists and engineers to transform models of social insect collective behavior into useful optimization and control algorithms. Also, swarm-based traffic simulation is used by engineers to predict and plan efficient traffic systems and reduce pollution. Moreover, if we have knowledge of animals migration patterns we can prevent the destruction of their habitat by making these areas closed to hunting and deforestation.

For the above reasons and many others, understanding large scale group interaction is imperative to improving our society. Computational and mathematical work has made it possible for simulations and models of these aggregations. We will attempt to create a mathematical model of these self-organized animal groups. We have chosen to model the behaviors and leadership patterns of a flock of birds. We will be using the computer matrix laboratory program called MATLAB. This program allows us to create a simple artificial organism swarm in a three dimensional space, given no interaction criteria at all. It also allows for the use of codes to model our research and visualize our assumptions. We will also reference the research and models of Couzin and Stefan, whose work will set the tenor for our model.

The motivation behind the research is to understand, mathematically, how a swarm can stay together and what rules are present for basic swarm procedures. Most importantly, we will focus on the connections and predictions between systems of local rules and their outcome configurations or vice versa. We are also interested in what configurations will give us different systems of rules, as well as what is necessary to implement leadership and swarm control. Throughout the semester we have developed and tuned our model through a series of milestones and challenges presented to us to understand and further explore our model. In this report we will explain how we developed our current mathematical model through these milestones.

## II. RELATED WORK

In [1], Couzin et.al. investigated the spatial dynamics of animal groups such as fish schools and animal flocks, and presented a self-organizing model of group formation in three-dimensional space. In their model, each individual member divided its vision range from inside to outside into three separate zones, namely, zone of repulsion (zor), zone of orientation (zoo) and zone of attraction (zoa). Members will avoid any other members in their zor, while move along the members in zoo, and move toward the members in zoa. The resulting velocity  $V_i$  of corresponding behaviors of animal  $i$  at time  $t$  related to other totally  $n_r + n_o + N_a$  animals ( $n_r, n_o, n_a$  are the number of animals in its zor, zoo, zoa, respectively) in its three zones is defined as follows:

$$\text{zone of repulsion (zor)} \quad d_r(t + \tau) = - \sum_{j \neq i}^{n_r} \frac{r_{ij}(t)}{|r_{ij}(t)|} \quad (1)$$

$$\text{zone of orientation (zoo)} \quad d_o(t + \tau) = \sum_{j=1}^{n_o} \frac{v_j(t)}{|v_j(t)|} \quad (2)$$

$$\text{zone of attraction (zoo)} \quad d_a(t + \tau) = \sum_{j \neq i}^{n_a} \frac{r_{ij}(t)}{|r_{ij}(t)|} \quad (3)$$

Here in equation (1),  $c_i$  and  $c_j$  stands for the position of animal  $i$  and its neighbor  $j$ .  $r_{ij} = (c_j - c_i)/|(c_j - c_i)|$  is the unit vector in the direction of the animal's neighbors.  $d_r(t + \tau)$  is the resulting vector guides animal  $i$  moving away from the neighbours that are too close to itself. In equation (2),  $v_j(t)$  is the moving direction of neighbor  $j$ , and the resulting vector  $d_o(t + \tau)$  allows animal  $i$  to align itself with its surrounding neighbors. In equation (3), the resulting vector  $d_a(t + \tau)$  allows animal  $i$  to orient itself toward the flock in case it strays too far. Finally, if  $|d_r(t + \tau)|$  (length of vector  $d_r(t + \tau)$ ) is not zero, then  $V_i = \frac{d_r(t+\tau)}{|d_r(t+\tau)|}$ ; Otherwise,  $V_i = \frac{d_o(t+\tau)+d_a(t+\tau)}{|d_o(t+\tau)+d_a(t+\tau)|}$ . Through extensive simulations, their model explains the formation of several collective behaviors and demonstrates the occurrence of transitions between these collective behaviors. In addition, their model also revealed the generation and maintenance of spatial positioning within animal groups.

In [2], Couzin et.al. furthered their work and studied the problem of effective leadership and decision making in moving animal groups. The authors proposed an individual-based decision making model based on the ability of group individuals to modify their motion on the basis of that of local neighbors. In addition to the rules of three zones in [1], the informed members (leaders) also had certain intention to move toward the destination. Their model explained that how consensus decision about moving direction can be made in a large group where only a small portion of the members are aware of the accurate destination. Simulation results demonstrated the correctness and merits of their model.

In [3], Stefan et.al. investigated the behaviors of honey bees and develop a distributed model to explain the existence of leadership in honey bee swarm. In their model, bees without knowledge of destination are incline to move along their neighbors, specifically, bee are more incline to move along the bees fly faster than other bee. For the bees that are aware of the correct destinations, they repeatedly fly more quickly than other bees through the entire group toward the destination. Eventually they lead the whole group to the destination without ever having explicitly announced their identity and the destination. Simulation shows that a small percentage of leaders (about 5%) can effectively guide the group.

In [4], Parrish and Edelstein-Keshet discussed the properties, characteristics, advantages and disadvantages of aggregations. They also investigates whether all emergent properties of animal aggregations are functional or if some are simply pattern. [4] was a very helpful resource as we analyzed the central issues of our swarm project, specifically with predicting all possible configurations and if it was possible to have effective leadership in a swarm. Factors such as elfish herdsand selfish individuals are expanded upon, as well as how extremes in the size of aggregations are likely to fail. These topics as well as many others discussed in this article demonstrate all of the different variables that aggregation is exposed to.

In [5], Toner et.al. studied the swarming behavior seen in flocking birds. By using a general rule for bird motion, they studied three main phases of flocks. The general motion rule is dependant on the amount of bird neighbors, or density of animals in a given area. Since no two birds move the same, the iteration of motion is randomized for the direction angle taken. This work goes in great detail to describe how they used previously discovered Navier-Stokes continuity equations, Vicsek Algorithm, and Mermin-Wagner theorem with the biological theory of what happens in flocks. This work not only goes into individual flight at different phases, but also the flock boundaries and what happens when certain things are introduced.

In [6], Topaz and Bertozzi use Couzin's work in Collective memory and Spatial Sorting in Animal Groups [1] to establish an understanding of the swarming in two dimensions. It seems the main focus of paper [6] is to differentiate from the individual types of swarming models. This was a valuable resource in that it serves as a summary of the historically major models. It also expands on the differences between models and how they work compared to one another. This was useful in understanding what is theoretically going on, explaining the differences and giving a two dimensional approach based on numerous theories and models.

In [7], Couzin and Franks developed an individual-based general model of ant behavior considering the abilities of ants to detect and avoid colliding with respect to local pheromone concentration. Simulation results demonstrated that their model can lead to a collective choice of direction and the formation of distinct traffic lanes that minimize congestion in ant swarms.

Although brief, [8] provided some useful knowledge on collective motion behavior. The most notable piece of information in paper [8] is that there is a critical density at which collective motion begins. While this critical density is dependent on a number of factors, it is none the less a very important concept. This is a very complex idea and paper [8] did not provide in depth information about slight density changes and how it would affect a swarm; however [8] did note that a small increase in density could result in abrupt changes in the collective motion.

### III. MILESTONE ONE: BEST PAPERS FOR THE PROJECT

The first milestone was simply a review of literature research. We believe that Dr. Couzin’s papers [1] and [2] are most related to all of the milestones for the following reasons.

- Dr. Couzin’s models are localized models and they work well in both 2D dimensional plane and 3D dimensional space for different tasks, such as forming patterns, moving towards destinations, etc.
- Dr. Couzin’s models are not specialized models for a particular species of animals, but are generalizations of all animals that exhibit aggregation behavior.
- Dr. Couzin’s models are simple and easy to implement in MATLAB.
- Weighted parameters in Dr. Couzin’s models can be changed easily for different behaviors in various swarm investigations.

### IV. MILESTONE TWO: MILLING PATTERNS

For the second milestone we were to develop a system of artificial organisms that organizes itself into a circle that represented a swarm milling behavior. The model our team used was an individual based model. An individual based model was very useful in studying these swarm groups, and showing that group leadership is not necessarily needed to reach the desired solution. The individual based model provides each animal with a set of rules to follow. Given certain inputs, the model can control the social behavior of all animals included in the swarm.

#### A. Assumptions

To create our models we first made a few key assumptions. The assumptions made for all of our codes are listed below:

- All animals move at a constant speed (All Models)
- Animals know which animals are leaders (Model 1)
- Leaders know a predefined circle to travel (Model 1 + 2 + 3)
- Three zones exist (ZOA, ZOR, ZOO) (All Models), and animals can recognize each other (Model 1+2+3)

#### B. Model3 for Milling Pattern

(1)Chasing Model: In this model, given a group of  $n$  animals, we let each animal  $a_i$  have a predefined leader  $a_{i-1}$ . The first animal  $a_1$  follows the leader animal  $a_n$ . As a result the animal group virtually forms a predefined group. For animal  $a_i$ , its velocity are defined as the following functions.

$$V_i = \alpha V_{i1} + \beta V_{i2} \quad (4)$$

Here,  $V_{i1}$  is calculated according to the rules of three zones in [1].  $V_{i2}$  is the vector towards it’s leader animal  $a_{i-1}$ . Variables  $\alpha$  and  $\beta$  can be selected to weigh the importance of the two vectors, which therefore affects the final behavior of the animal group.

(2)Group Chasing Model: In this model, given a group of  $n$  animals, we split the group into certain numbers of sub-groups. Also, in each sub-group, we elect exactly one animal as the leader and let the rest in this sub-group follow the leader. Moreover, we also predefined a virtual circle among the sub-group leaders in the way of the Chasing Model. For animal  $a_i$ , its velocity is defined as the following functions. The difference between the Chasing Model and Group Chasing Model is that the Group Chasing Model has a hierachy structure, and therefore can be used for animal groups containing a large number of animals.

$$V_i = \alpha V_{i1} + \beta V_{i2} \quad (5)$$

Here,  $V_{i1}$  is calculated according to the rules of three zones in [1].  $V_{i2}$  is the vector towards its leader animal  $a_{i-1}$ . Variable  $\alpha$  and  $\beta$  can be selected to weigh the importance of the two vectors and therefore affect the final behavior of the animal group.

(3)Leader Model: In this model, given a group of  $n$  animals, we select a certain percentage of animals and let them form a virtual circle, as we did in the Chasing Model. The rest animals in the group adjust their velocity according to the rules of the three zones [1].

(4)Converge Model: In this model, given a group of  $n$  animals in a 2D plane, we define a virtual force on each animal, which acts toward the center of the group. For animal  $a_i$ , its velocity is defined as following functions.

$$V_i = \alpha V_{i1} + \beta V_{i2} \quad (6)$$

Here,  $V_{i1}$  is calculated according to the rules of the three zones in [1].  $V_{i2}$  is the vector towards the center of the group. Variable  $\alpha$  and  $\beta$  can be selected to weigh the importance of the two vectors and therefore affect the final behavior of the animal group.

### C. Observations

Figure 1 demonstrates the performance of all of our models.

### D. Strength And Weakness

(1) Chasing Model. This model works well in both 2D and 3D scenarios, but it is not realistic for modeling the animal groups in nature since we are assuming the animal would be able to recognize the leaders. Moreover, once the number of animals in the group becomes large, the resulting milling topology of the animal group will be twisted.

(2)Group Chasing Model. This model is the extension of the Chasing Model. It works well in both 2D and 3D scenarios, and it can support animal groups with a large number of animals. However, it is also not realistic for modeling the animal groups in nature.

(3) Leader Model. This model works well in both 2D and 3D scenarios, and we beleive it is very realistic for modeling the animal groups in nature because the followers cannot differentiate the leaders. Also, the number of leader animals can be chaged to support animal groups with a large number of animals. The weakness of this model is that there is a requirement of the percentage of leaders to form the milling pattern.

(4)Converge Model. This model works well only in 2D scenarios, and we beleive it is very realistic for modeling animal groups in nature. Moreover, this model can support animal groups with a large number of animals.

## V. MILESTONE THREE: MOVE TOWARD A DESTINATION

The third milestone aims to design a simple system of artificial animals that organizes itself into a swarm with a minimum number of leaders that move to a specific location. All animals must be the same except for those (the leaders) with some knowledge of the desired location. All animals must appear identical to one another. In other words, the algorithm cannot use information such as animal one is the leader - follow it. The only dynamic behavior inputs permitted are the relative positions of the other animals.

The model our team used was a leader based model, where a small number of leaders directed the entire swarm. In this model, the leaders are the only informed individuals and fly to a specific location. All other members of the swarm are uninformed and governed only by Couzins three zone rules. Given fixed coordinates of the destination, the swarm will progress towards that point.

### A. Assumptions

To create our model we first made a few key assumptions. Many of these assumptions are similar to our assumptions in the second milestone, because this model is a slightly modified version of our Model 3 used in milestone 2.

- All animals move at a constant speed.
- Leaders know where the destination is.
- Leaders are unknown to rest of swarm.
- At least 1 leader exists.
- Three zones exist (zoo, zoa, zor) and animals can recognize the position of others in their three zones.

### B. Models For Effective Leadership

For each animal, we divide its vision range into three zones. If the animal has the information of the desired destination, it will try to move towards the destination. To balance the rules of three zones and the intention to move to the destination, for, animal  $i$ , its final velocity vector is defined as:

$$V_i = \alpha V_{i1} + (1 - \alpha) V_{i2} \quad (7)$$

Here,  $V_{i1}$  is the sub-vector decided by the rules of three zones.  $V_{i2}$  is the sub-vector toward the destination. For leaders,  $\alpha$  is a positive value between 0 and 1. For non-leader animal, we define  $\alpha = 1$ .

### C. Observations

We implemented our model using MATLAB 7.2. To better observe the movement of each animal, we did not use the Z-axis value of each animal and projected the movement of the whole group onto the X-Y plane. We conducted a series of simulations with different configurations for the values of  $\alpha$  and  $\beta$ , as well as a different percentage of leaders. Figure 2 displays the entire migration process of an animal group with 1 leader and 49 followers.

*Observation One : value of  $\alpha$  and  $\beta$ .* We tried different combinations of  $\alpha$  and  $\beta$ . The larger the value of  $\alpha$ , the slower a consensus decision towards the destination is reached. However, with a larger value of  $\alpha$ , the leaders will stay within the swarm making classification difficult. When  $\beta$  is larger than  $\alpha$ , the entire group can quickly adapt its direction towards the destination. In this scenario the leaders move towards the front of the group, providing clear classification between the followers and leaders.

*Observation Two : the number of animals.* The more animals the group contains, the slower their consensus decision toward the destination can be made. Also, we notice that the value of the zone of orientation is critical in making the consensus decision. There is a threshold value of the zoo for making a consensus decision. For example, when the animal group contains 100 animals, the value of zoo must be larger than 11. Moreover, the more animals the group contains, the larger the threshold values is.

*Observation Three : percentage of leaders.* For a group of 100 animals with  $\alpha = \beta = 0.5$ , any percentage of leaders (from 1 to 100) can eventually lead the whole group to the destination. But the movement in the entire process is quite different. For example, when there is only one leader, it takes a longer time for the whole group to finally find the correct direction. Specifically the particular leader is outside of the swarm most of the time. When there are five leaders the behaviors of the entire group are much better, the group can quickly tune their direction toward the destination, and the leaders will stay in the group.

*Observation Four : behavior when the group gets to the destination.* For a group of 100 animals with  $\alpha = \beta = 0.5$ , we find that when the group reaches the destination, the leaders will stay in a swarm and fly randomly at the destination, while the non-leaders will fly in a big circle around the destination. Thus the more the leaders that are present, the shorter the radius of the circle will be.

#### D. Strength And Weakness

We summarize the strengths and weaknesses of our model as follows:

Strengths:

- Our model works in both 2D dimensional plane and 3D dimensional space.
- Our model only needs a small percentage of leaders to get the swarm to the specified location.
- Our model allows us to easily distinguish the different behaviors of leaders and followers.
- In our model, animals do not recognize each other, similar to nature.
- Weighted parameters in our model can be changed easily for different behaviors for further swarm investigation.

Weaknesses:

- At destination, leaders stay close to specified location while the other follower animals fly around the point.
- The zone of orientation must be larger than the threshold value to get good results.
- Since all leaders are in the front of the swarm, introducing an obstacle or predator could split the flock (in looking at milestone four).

### VI. MILESTONE FOUR: PREDATOR AND PREY

Our challenge for the fourth milestone is similar to our previous milestone except that now we are introducing a predator to our model. For this milestone we are to create a simple system of artificial animals that organizes itself into a swarm with a minimum number of leaders that move to a location specified by Dr. Rossi, while avoiding a predator. Requirements for this milestone are that all animals must appear identically to one another and the only dynamic behavior inputs permitted are the relative positions of other animals and the possible position of the predator.

Our model is a leader based model, where a small number of leaders direct the entire swarm. In this model, the leaders are the only informed individuals and fly to a specific location. All other members of the swarm are uninformed and governed only by Couzins three zone rules. Given fixed coordinates of the destination, the swarm will progress towards that point. Each bird is capable of detecting the existence of the predator when it is close, and has the ability to move away from it.

#### A. Assumptions

To create our model, it was necessary to make a few key assumptions. Many of these assumptions are similar to those in previous milestones. To implement the predator we have introduced a predator model. This has created some new assumptions for the predator and its interaction between itself and its prey. Our Assumptions are listed as follows:

- Each bird divides its vision range into three zones; ZOR, ZOO, and ZOA. Each bird reacts to its neighbors in the zones according the rules defined [1].
- Each bird also has an additional zone for reacting to the predator. This zone is named the zone of avoidance (ZOAV).
- Leader birds are informed about the destination, while followers are not aware of the destination at all.
- All the birds cooperate with each other through local rules without explicitly announcing their identities (leader or follower).
- All the birds move at a constant speed.
- Predator has global knowledge of the positions of all the birds.
- Predator has an effective zone. This is called the zone of death (ZOD). The predator is able to kill all birds within this zone.
- Predator flies faster than the birds, but it has an energy constraint. The Predator stops when it depletes its energy.

### B. Models For Predator And Prey

**Predator Model:** One major challenge in this milestone was to develop a proper predator model. The predator cannot be too weak that it cannot catch any birds, nor can the predator be too powerful and kill all of the birds. Therefore, we define that the predator can fly 33% faster than the birds within certain amount of distance. The predator model consists of three parts: direction, speed as well as constraint, and catching. The predator first finds a target in the bird flock and flies directly towards its target. Secondly, the predator can fly faster than the birds. However, the predator can fly only as long as its energy permits. Its energy can support it to fly for a fixed distance,  $D$ . Finally, to model the catching process, we define a zone of death (ZOD) for the predator; the predator has the ability to kill all of the birds in its ZOD during the chasing process.

**Prey Model:** In our prey model, each bird (leader and follower) divides its vision range into three zones, and will react to its neighbors that are within its zones according to the rules defined in [1]. Leader birds have the information of the desired destination and will also try to move towards the destination. Moreover, all of the birds (leader and follower) will try to avoid the predator by flying away from it when they detect its existence in their zone of avoidance (ZOAV). To balance all these factors in our model, we gave each factor a weight. For a follower  $i$ , its final velocity vector is defined as:

$$V_i = (1 - \gamma)V_{i1} + \gamma V_{i3} \quad (8)$$

Here,  $V_{i1}$  is the sub-vector decided by the rules of three zones.  $V_{i3}$  is the sub-vector to avoid the predator.  $\alpha$  is a non-negative value for modeling the intention to avoid the predator. The closer the bird and predator are, the higher  $\gamma$  is. Specifically,  $\gamma$  is defined as: If  $d > radius(ZOAV)$  then  $\gamma = 0$ ; Otherwise,  $\gamma = \frac{radius(ZOAV) - d}{radius(ZOAV)}$ . Here,  $radius(ZOAV)$  stands for the radius of the zone of avoidance.  $d$  stands for the distance between the predator and the bird  $i$ . For a leader animal  $a_i$ , its final velocity vector is defined as:

$$V_i = (1 - \gamma)(\alpha V_{i1} + \beta V_{i2}) + \gamma V_{i3} \quad (9)$$

Here,  $V_{i1}$  is the sub-vector decided by the rules of three zones.  $V_{i2}$  is the sub-vector toward the destination. For leaders,  $\alpha$  and  $\beta$  are positive values between 0 and 1, moreover, we have  $\alpha + \beta = 1$ .  $V_{i3}$  is the sub-vector to avoid the predator,  $\gamma$  is the same as the one in the model for follower.

### C. Observations

We implemented our model using MATLAB 7.2. To better observe the movement of each animal, we did not use the Z-axis value of each animal and projected the movement of the entire group onto the X-Y plane. We conducted a series of simulations with different configurations of the values of  $\alpha$ ,  $\beta$ ,  $radius(ZOAV)$  and  $radius(ZOD)$ , as well as a different percentage of leaders. Figure 3 demonstrate the whole process of attacking, avoiding, and moving toward the destination.

*Observation One : value of  $\alpha$  and  $\beta$ .* We tried different combinations of  $\alpha$  and  $\beta$ . We found that in order to enable the survival of the flock to the destination,  $\alpha$  should be significantly larger than the  $\beta$ . Otherwise, the leaders will fly away from the group to destination, while the followers will get lost because there is no leader for them to follow to the destination. We observed that the larger  $\alpha$  is, the less possible it will be for the entire group to get partitioned after the attack of predator. When the  $\alpha > 0.9$ , the leaders will always lead the group to the destination.

*Observation Two : the number of animals.* The more birds the group contains, the more leaders the group will need to fly to the destination after the attack of the predator. This is because leaders must remain alive in order to lead them to the destination. If the number of the leaders is small, it is very likely that most of the leaders will die in the attack, and that the rest of leaders may not be enough to lead the whole group (the group also becomes sparse after the attack and probably need more leaders). Also, we notice that the value of the zoo is critical in making a consensus decision. There is a threshold value of zoo for making a consensus decision. For example,

when the animal group contains 100 animals, the value of  $z_{00}$  must be larger than 11. Also, the more animals the group contains, the larger the threshold value will be.

*Observation Three : zone of avoidance.* We find that the size of the zone of avoidance is also critical for the whole group to fly to destination after the attack. There is a clear tradeoff between the number of birds killed in the attack and the possibility that the whole group may still be able to get to the destination. If the zone of avoidance is too large, fewer birds will die in the attack, but the whole group may become too sparse and some bird will get lost. On the other hand, if the zone of avoidance is too small, birds can still get to the destination at the expense of a large amount of birds sacrificed in the attack..

*Observation Three : attack direction of the predator.* We find that the attack direction of the predator also affects the number of birds the predator can kill. For example, if we define one side of the flock towards the destination as the front, while the opposite side is defined as the rear; we find that predator can kill more birds if it attacks the whole group from the front side.

*Observation Four : behavior when the group gets to the destination.* We find that when the group reaches the destination, the leaders will stay in a swarm and fly randomly at the destination, while the non-leaders will fly in a big circle around the destination. Thus, the more the leaders there are, the shorter the radius of the circle will be.

#### D. Strength And Weakness

We summarize the strengths and weaknesses of our models as follows. Strengths:

- Our model works in both 2D dimensional plane and 3D dimensional space.
- Our model only needs a small percentage of leaders to get the swarm to avoid the predator and get to the specified location.
- Our model can help us to easily distinguish the different of behavior of leaders and followers.
- In our model, animals do not recognize each other, much like in nature.
- Weighted parameters in our model can be changed easily for different behaviors for further swarm investigation.

Weaknesses:

- At destination, leaders stay close to specified location while the other follower animals fly around the point.
- The zone of orientation must be larger than the threshold value to get good results.
- Zone of Avoidance is a tradeoff between the number of birds killed in the attack and possibility that the whole group can get to the destination.

## VII. MILESTONE FIVE: BOUNDARY DETECTION

For the final milestone, we are to have a swarm of identical animals locate a given contour shape defined by a function  $f(x, y, z) = 0$ . The isosurface will be continuous and compactly supported. The only dynamic behavior inputs permitted are the relative positions of the other animals.

#### A. Assumptions

Aside from the assumption in previous milestones, we make following new assumptions for this milestone.

- A very big shape in 3D space to detect.
- All birds are identical to each other.
- Birds coordinate with each other through local rules (rules of three zones).
- Only one leader exists in the bird flocking.
- The leader is able to detect the boundary (reads the value of  $f(x, y, z)$ ).
- No memory of visited place.

### B. Models For Boundary Detection

We developed two different heuristic models for boundary detection, namely ping pang ball model and orbit model.

(1) Ping Pang Ball Model: Initially, the leader animal  $a_i$  moves at velocity  $V_{i1}$ . Whenever the leader animal hits the boundary, it changes its velocity according to following equations.

$$V_i = -\alpha V_{i1} + (1 - \alpha)V_{i2} \quad (10)$$

Here,  $V_{i2}$  is a random vector.  $\alpha$  is a positive value between 0 and 1 for tuning the weight of vectors  $V_{i1}$  and  $V_{i2}$ .

(2) Orbit Model: Initially, the leader animal  $a_i$  moves at velocity  $V_{i1}$ . Whenever the leader animal hits the boundary, it changes its velocity according to following equations.

$$V_i = \alpha V_{i1} + \beta V_{i2} + \gamma V_{i3} \quad (11)$$

Here,  $V_{i2}$  is an attraction vector constraining the animal  $a_i$  from leaving the boundary. In implementation, the animal  $a_i$  will pick up a random point on the isosurface, and  $V_{i2}$  is the vector towards this particular point.  $V_{i3}$  is a random vector.  $\alpha$ ,  $\beta$  and  $\gamma$  are positive values between 0 and 1 for tuning the weight of vectors  $V_{i1}$ ,  $V_{i2}$  and  $V_{i3}$ . Specifically, we define  $\alpha + \beta + \gamma = 1$ .

### C. Observations

Figure 4 shows the behavior of leader animal in Ping Pang Ball Model. Figure 5 shows the behavior of the leader animal in the Orbit Model. Figure 6 compares the results of these two models. We can see in the Ping Pang Ball Model that the leader animal detects discrete regions in the boundary; in the Orbit Model, the leader animal always detects continuous regions in the boundary.

### D. Strength And Weakness

We summarize the strengths and weaknesses of our models as follows.

#### *Strength*

- Simple localized models work well in simulations.
- Suitable for both 2D and 3D scenarios.
- Birds coordinate with each other through local rules (rules of three zones).
- Given enough time, our models can detect all of the points on the boundary with high probability.

#### *Weakness*

- Heuristic models without guarantee of the completion.
- Most travel is wasteful in ping pang ball model.

## VIII. CONCLUSION AND WHAT WAS LEARNED

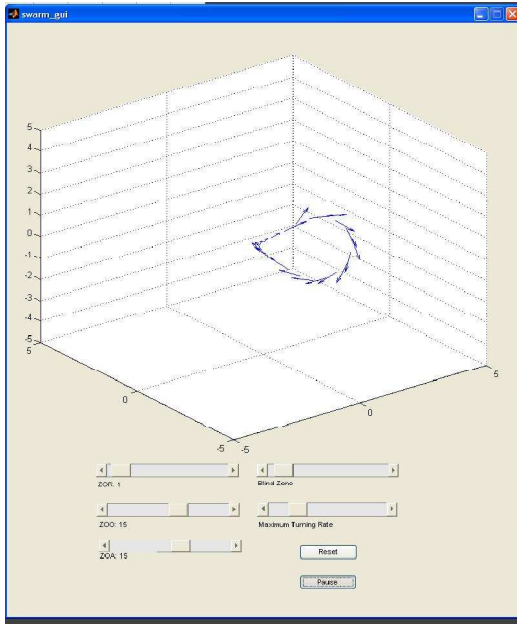
Through research and mathematical modeling our team has investigated the group behavior of swarming organisms in a variety of different scenarios. These scenarios include milling, leading, finding a destination, avoiding a predator, and finding a specific contour plane. The majority of the mathematics behind our modeling has been based on previous research from Couzin. Couzin has come up with the idea that there are three zones (ZOA, ZOO, ZOR) that govern swarm behavior. We have used these three zones along with our own inputs to control the swarm models we have created. With all of our models we kept the percentage of leaders low and identities of all individuals unknown. These are two characteristics that are often observed in nature and had to be integrated for a realistic model. Through studying previous research and testing mathematical models of swarm behavior our team has learned many things about swarming organisms and the importance of modeling natural behavior. We better understand survival and travel actions witnessed in organisms, and can now better predict what these actions will be in a given situation. Additionally we now know that leader behavior varies depending on the animal. Some will use physical or chemical signals, while others will steer the group by their own movements. Many swarms require very few leaders to organize and move the group, some as few as 5. This was one characteristic that we

were able to successfully model in our code. We could easily guide the swarm with 51are in a group, the more efficient the group can move. Although theoretically this makes sense, it is a difficult idea to model. We were able to guide our simulated swarms with as few as one leader, however it was far from efficient (time and direction to destination).

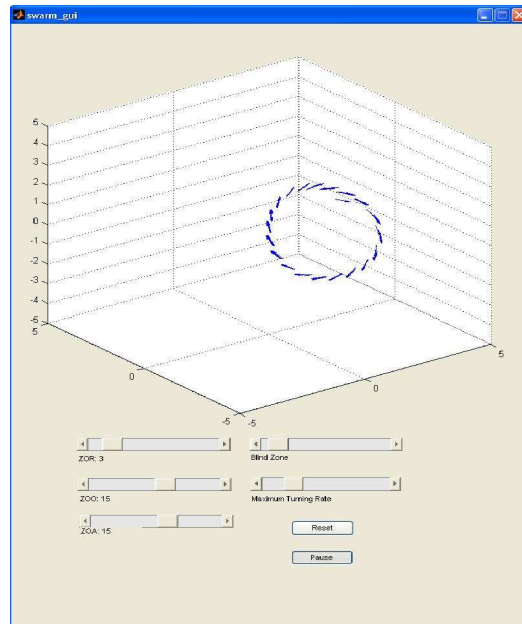
Modeling swarms has many practical uses in the modern world. The military has been trying for many years to implement drones to reduce the loss of human life. To create an army of unmanned vehicles, with little human input will require mathematical modeling similar to our swarm models. These models ensure that the vehicles will make the correct movements, avoid obstacles, reach the destination, and not collide with other vehicles. Swarm modeling can also be used to predict movement patterns on crowded streets and help alleviate the problem. This is especially important in an emergency situation when lives are at stake. Although it may be years before these real world issues are solved, our mathematical modeling serves as a good first step towards finding a solution

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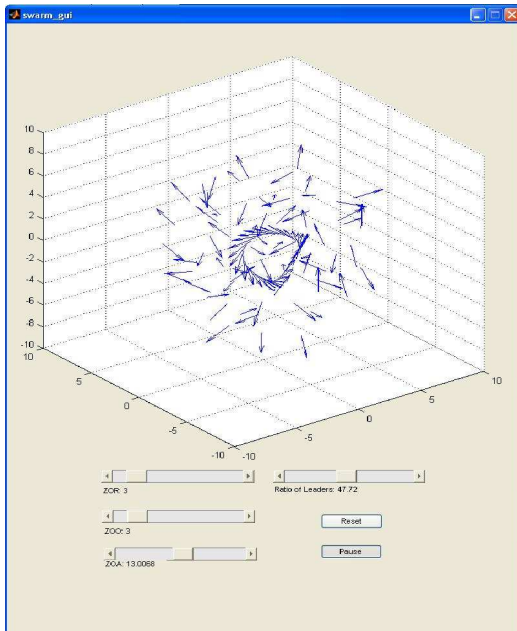
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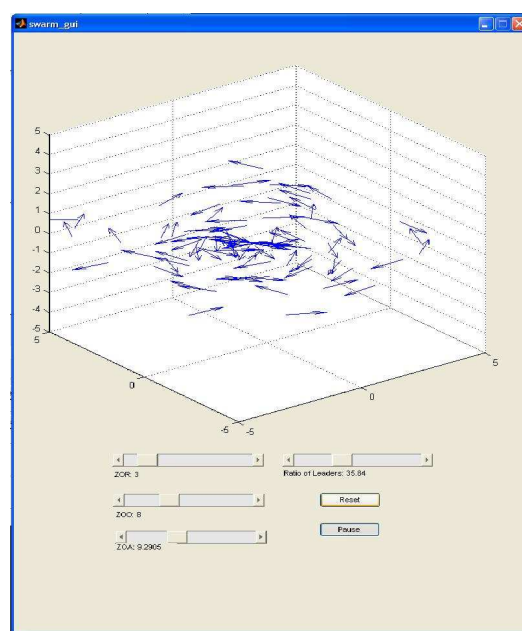
(a)



(b)



(c)



(d)

Fig. 1. Milling patterns of animal group. (a) Chasing model for the animal group with 25 animals. (b) Group chasing model for the animal group with 100 animals. (c) Leader model for the animal group with 100 animals. (d) Converge model for the animal group with 100 animals.

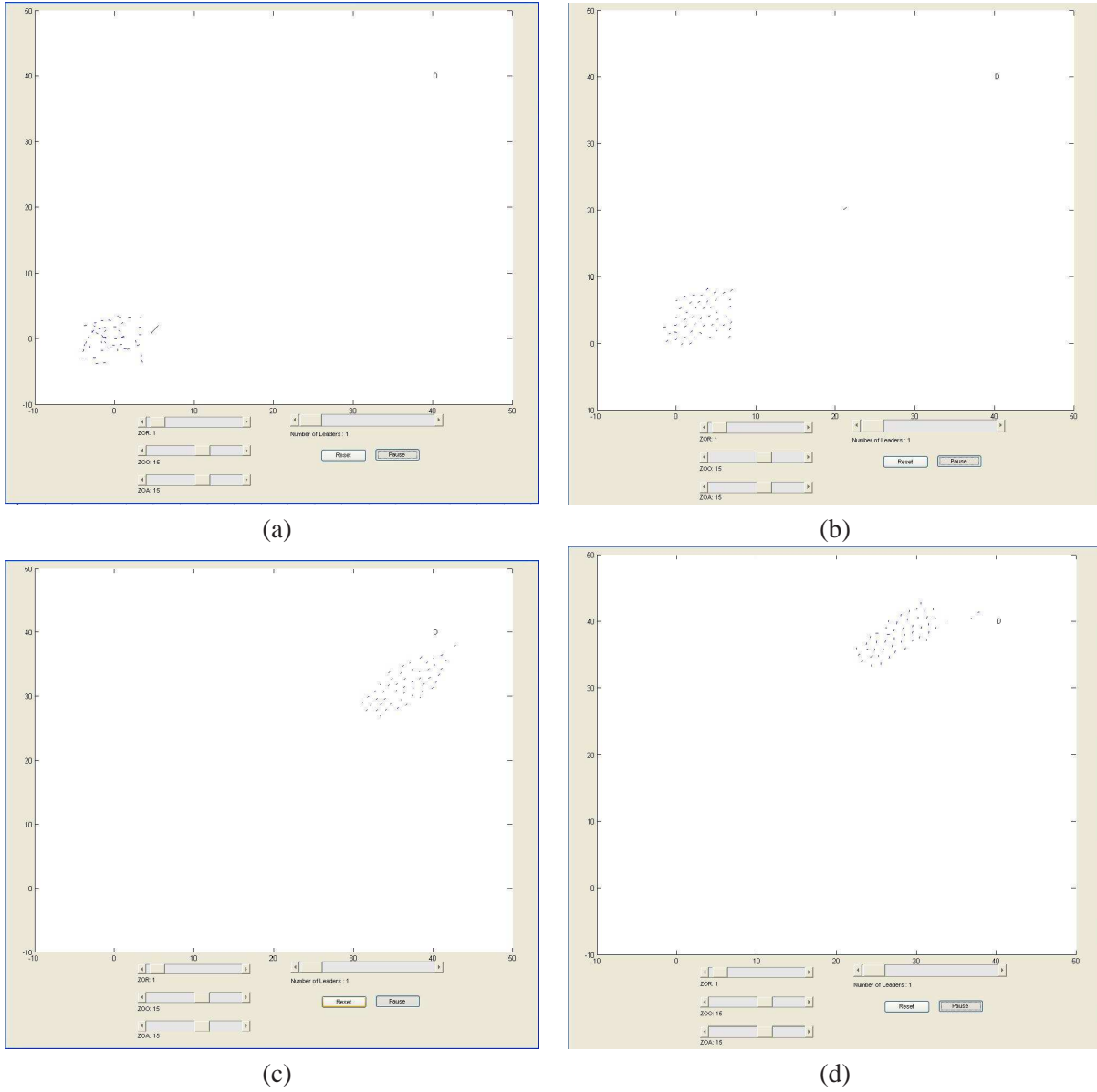


Fig. 2. 1 leader animals and 49 follower. Black arrow stands for leader animal while blue arrows stand for followers. Letter D in the figure shows the position of the destinations. (a) Initial topology of the animal group. (b) The whole group get the consensus decision toward the destination. (c) The whole group get to the destination (d) The whole group mill around the destination.

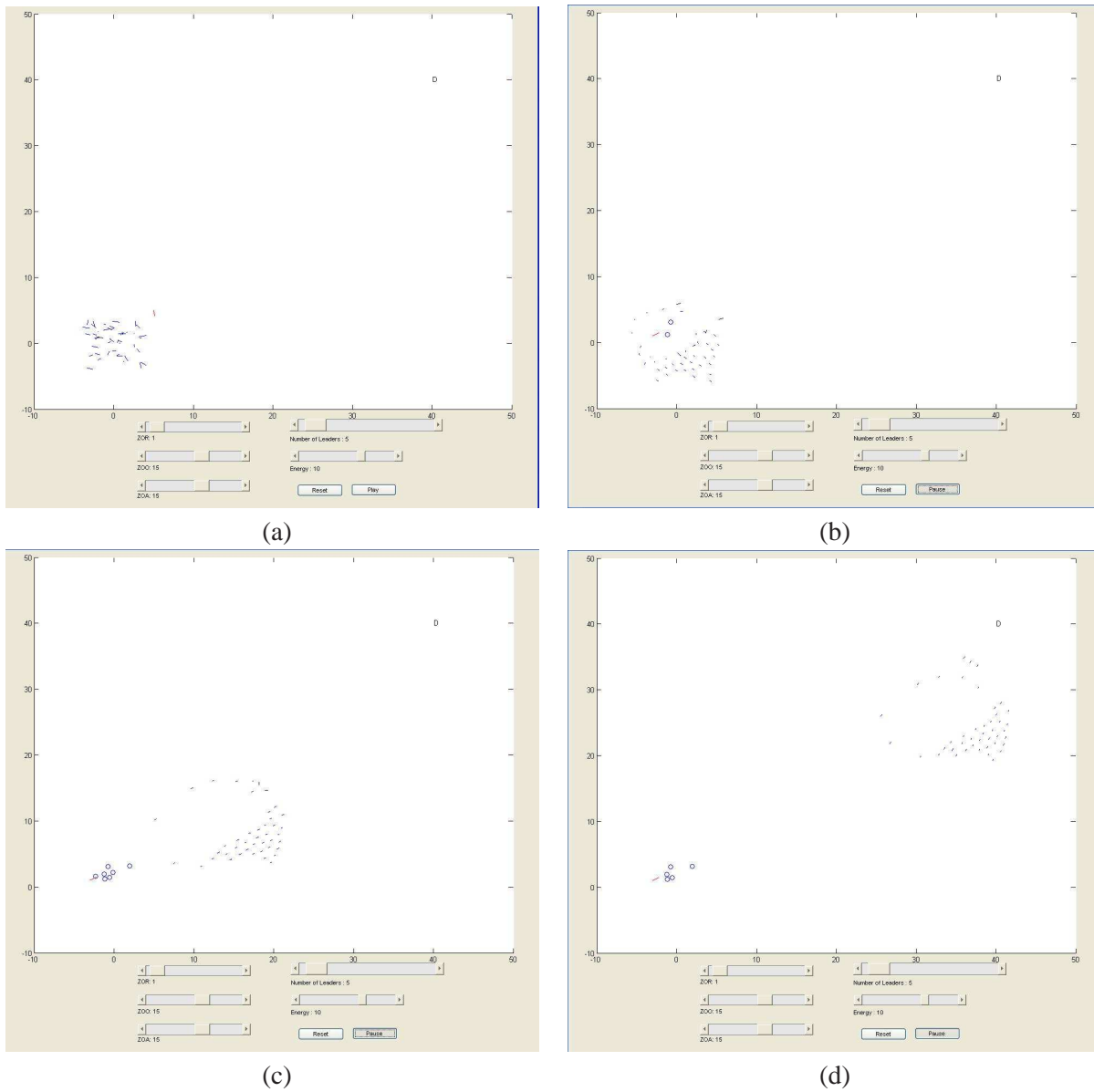
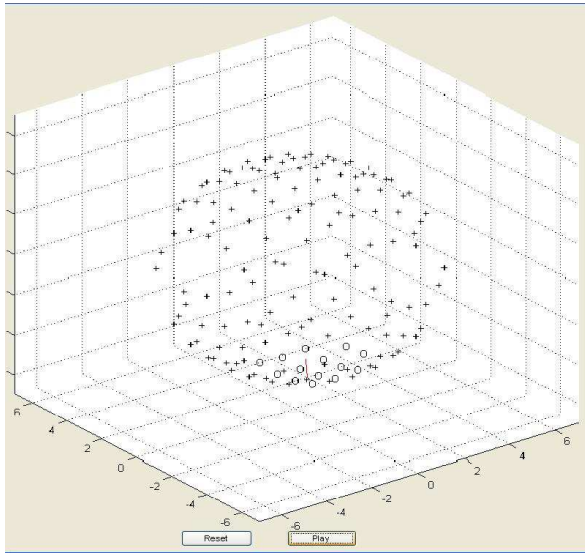
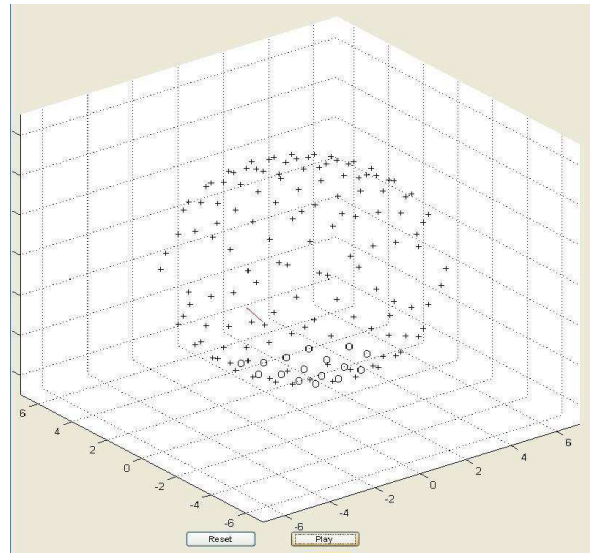


Fig. 3. 1 predator with energy to move 10 unit distance. Animal group contain 5 leaders and 45 followers. (a) Initial topology of the animal group and predator. (b) Predator attacks the animal group. (c) Animal groups reunited after the attack. (d) Animal group move toward the destination.

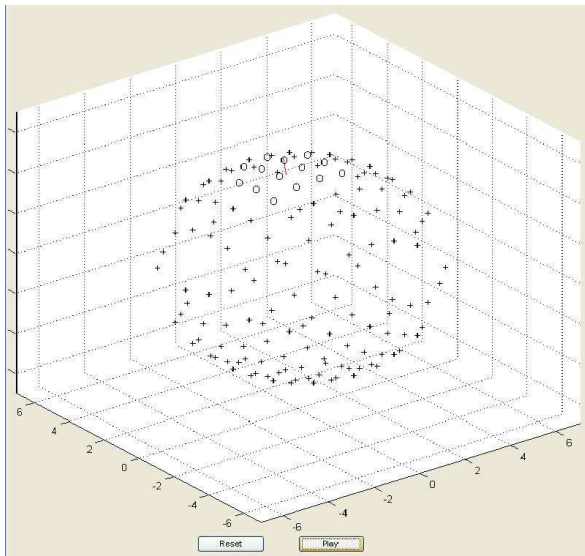


(a)

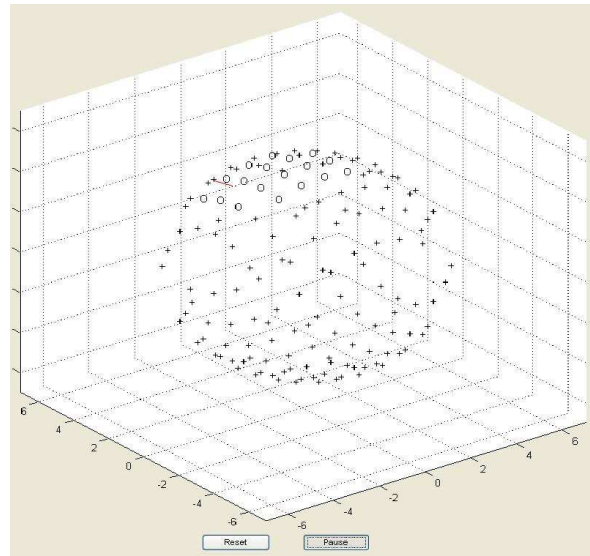


(b)

Fig. 4. Ping Pong Ball Model (a) Before the leader hits the boundary. (b) After the leader hits the boundary.

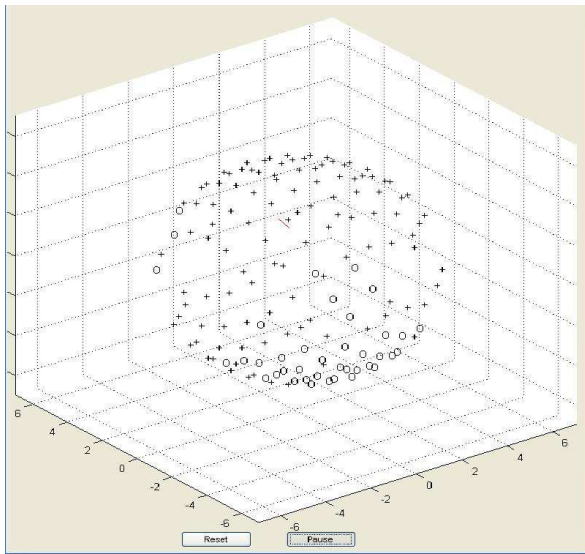


(a)

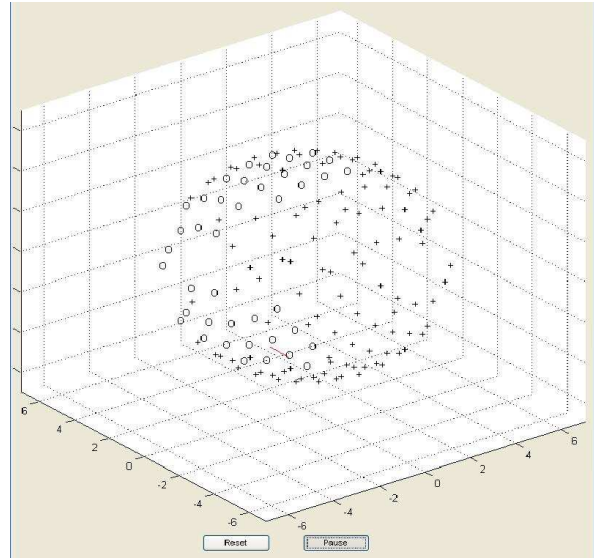


(b)

Fig. 5. Orbit Model (a) Before the leader hits the boundary. (b) After the leader hits the boundary.



(a)



(b)

Fig. 6. Boundary detection after 50 time steps (a) Ping Pong Ball Model (b) Orbit Model.