Performance Metrics of Collective Coordinated Motion in Flocks

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Abstract

Measurements of coordinated motion in flocks are necessary to evaluate their performance. In this work, a set of quantitative metrics to evaluate the performance of the spatial features exhibited by flocks are introduced and applied to the well-known *boids* of Reynolds. Our metrics are based on quantitative indicators that have been used to evaluate fish schools. These indicators are revisited and extended as a set of three new metrics that can be used to evaluate and design flocks.

Keywords. metrics, flock, behaviors, boids

Introduction

An intriguing collective phenomenon of nature is caused by animals moving as a coordinated unit, for example a flock of birds or a fish school. This phenomenon has attracted interest in various scientific fields such as biology, artificial life and artificial intelligence distributed, because the phenomenon suggests an intelligent organization that transcends the abilities of each individual (Camazine et al., 2003).

The coordinated collective movement has important applications such as virtual reality and computer animation. The flocks models are often used to provide realistic-looking representations of flocks, schools or herds. For instance, they are used in the Half-Life video game to model the flying bird-like creatures or in the film Batman Returns to model bat swarms and armies of penguins (Bajec and Heppner, 2009).

In addition, the flocks models can be used for direct control and stabilization of teams of simple Unmanned Ground Vehicles (UGV) or Micro Aerial Vehicles (MAV) in swarm robotics (Min and Wang, 2011; Saska et al., 2014). Also, they can be used in applications that require the coordinated action of multiple autonomous individuals such as flying robots (drones) used in collective search, agricultural monitoring and event surveillance (Vsrhelyi et al., 2014).

Other interesting applications where flock models has been applied is the automatic programming of Internet multi-channel radio stations and for optimization tasks (Ibáñez et al., 2003; Cui and Shi, 2009).

The measurement and evaluation of the collective performance of autonomous agents is an open issue (Navarro and Matía, 2009). A lot of work remains to be done in the development of indicators that capture important aspects of the collective dynamics of groups of autonomous entities based, for instance, on the goal achievement, the formation of spatial patterns, and the exploitation of resources.

The tune of values for the achievement of coordinated flocks is far from being trivial, because the parameters that influence the behaviors of the members of flock are closely interrelated. Performance metrics are the criteria that determine success in the behavior of a system. Therefore it is necessary to design objective performance metrics that allow discern that flocks behave better.

In this work we propose new metrics in order to capture the global performance, in spatial terms, of the flocks such that they can be used as a benchmark. Our metrics are based in quantitative indicators that have been used to characterize spatial features exhibited by a fish school: extension, polarization and frequency of collisions (Huth and Wissel, 1992; Zheng et al., 2005). These measures are revisited and extended in a set of three new measures: consistency in expansion, consistency in polarization, and quality.

Related Work

A seminal work that aims at reproducing the flock phenomenon is the model of coordinated collective motion proposed by Reynolds (Reynolds, 1987), where individual entities, generically known as *boids*, achieve realistic behaviors by the application of a set of basic rules. This model is used in this work to applied our performance metrics. Therefore, we review in detail this model in the next section.

In the area of biology, Huth and Wissel (Huth and Wissel, 1992) present a simulation of a school of fish. The behavior of each fish are attraction, repulsion, parallel orientation and search. Polarization and extension are proposed as descriptive metrics of a school. The polarization reflects the degree of alignment of the agents headings, if fish belonging to the school are oriented in similar directions a school has a small polarization. The extension reflects the degree

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

of cohesion that has a school, that is, how far the fishes are between themselves.

In the work of Huepe and Aldana (Huepe and Aldana, 2008) are compared three simple models that reproduce qualitatively the emergent swarming behavior of bird flocks or fish schools, by using of the metrics: polarization, local density and nearest neighbor mean distance. While the polarization (standard order parameters use in the flocks) behave equivalently in all cases, the local density and nearest neighbor mean distance introduced provide a more detailed description that can clearly distinguish the properties of swarming behavior.

In the work of Navarro and Matía (Navarro and Matía, 2009) a set of metrics that measures the performance of collective movement of mobile robots is proposed and discussed. The different metrics proposed cover several aspects of the characteristics of the collective movement including: those related to the area and shape of the group; the movement; and the positioning and orientation of its members.

In the work of Bajec et al. (Bajec et al., 2007) it is presented an artificial animal construction framework that has been obtained as a generalization of the existing bird flocking models. A set of metrics that can measure and judge the flocking behavior of a group of *boids* is presented and the metrics are used in a series of controlled experiments to evaluate the flocking behavior of *boids*.

The *boids* model

This work is based on a model of coordinated collective motion proposed by Reynolds in his classic article (Reynolds, 1987), which is inspired by the movement of flocks and schools. Entities belonging to a formation (birds, fish, etc.) were called by Reynolds generically as *boids*. Each *boid* apply a simple set of steering behaviors such as cohesion, separation and alignment, that govern their movement. A flock is the result of the interaction of each *boid* with its neighbors.

The set B of n *boids* b_i involved in the flock is denoted by formula 1.

$$B = \{b_i, i = 1, 2, \ldots, n\} \tag{1}$$

Each *boid* b_i has a position vector $\vec{p_i}(t)$ and a velocity vector $\vec{v_i}(t)$ that describe its motion in space in a time t. The force which adjusts the speed of the *boid* is typically an impulse generated by the same, so that impulse is limited in a scalar of maximum force denoted as f_m. In addition, *boids* are restricted to a maximum speed expressed as s_m. This speed limit is imposed by a gating of the velocity vector of the *boid*. In addition, the acceleration acquires a *boid* also depends on the inertia of the body expressed as a scalar quantity mass m_b.

The local space associated with each *boid* b_i is described by $\vec{f_i}(t)$, $\vec{s_i}(t)$ and $\vec{u_i}(t)$ which refer respectively to the vectors "forward"(x axis), "side"(z axis) and "up"(y axis). Where each *boid* has a local view of its environment called "area of perception"related to a steering behavior. The area of perception is determined by a radius r and a angle θ (field of view) where only neighbors who are in the area of perception are selected for calculating certain steering behavior (see Figure 1).

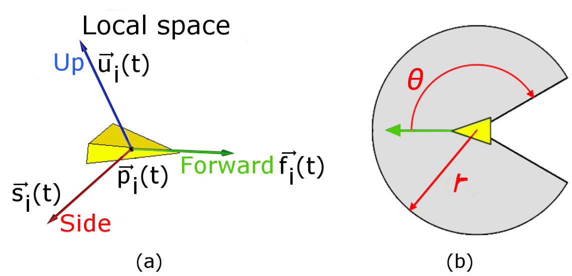

Figure 1: Figure (a) shows the local space of a *boid*. Figure (b) shows the area of perception of a *boid*.

The set of *boids* b_j perceived by the *boid* b_i is denoted P_i and is calculated as follows:

Step 1. Calculate distance, distance d_{ij} is determined from the *boid* b_i and *boid* b_j,

$$d_{ij} = \|\vec{p_j}(t) - \vec{p_i}(t)\| \tag{2}$$

Step 2. Calculate angle, the angle θ_{ij} is determined between the vector "forward"of *boid* b_i and the unit vector in the direction of the position of the *boid* b_j,

$$\theta_{ij} = \frac{180}{\pi} \arccos \left[\vec{f_i}(t) \cdot \left[\frac{\vec{p_j}(t) - \vec{p_i}(t)}{\|\vec{p_j}(t) - \vec{p_i}(t)\|} \right]^T \right] \tag{3}$$

Step 3. Calculate neighbors, determine if the distance d_{ij} is less than the radius r of *boid* b_i and angle θ_{ij} is within the angle θ of *boid* b_i, then the *boid* b_j belongs to its local neighborhood,

$$P_i = \{b_j \in B; \forall b_j : d_{ij} < r \wedge \theta_{ij} < \theta, j = 1, 2, \ldots, m\} \tag{4}$$

where m is the number of *boids* perceived by the *boid* b_i on its radius of steering behavior.

The steering behaviors of a *boid* b_i executed at time t are cohesion, $\vec{c_i}(t)$; separation, $\vec{s_i}(t)$; and alignment, $\vec{a_i}(t)$ where the areas of perception associated with these steering behaviors are determined by the radii and angles r_c, θ_c; r_s, θ_s; and r_a, θ_a respectively. In addition, the steering behaviors cohesion, separation and alignment are associated with the sets of *boids* b_j perceived C_i, S_i and A_i, respectively. The calculation of neighbors *boids* belonging to said sets is performed as in steps 1, 2 and 3 above.

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

The purpose of cohesion behavior is to move a *boid* towards the center of a group perceived within its neighborhood. If this steering behavior were uniquely applied, the formation would be gathered together in a region. The formula of cohesion, $\vec{c_i}(t)$ is expressed in (5), where m_c is the cardinality of the set C_i.

$$\vec{c_i}(t) = \left(\frac{1}{m_c} \sum_{\forall b_j \in C_i} \vec{p_j}(t) \right) - \vec{p_i}(t) \tag{5}$$

The purpose of separation behavior is to move a *boid* to avoid a collision with their neighbors and prevents agglomeration of formation. If only this behavior is applied, the formation dissipate. The formula of separation, $\vec{s_i}(t)$ is expressed in 6.

$$\vec{s_i}(t) = - \sum_{\forall b_j \in S_i} (\vec{p_j}(t) - \vec{p_i}(t)) \tag{6}$$

The purpose of alignment behavior is to move a *boid* in the same direction as their neighbors. The alignment behavior acts as a first heuristic to avoid collision, because when all *boids* of a formation move at the same velocity the risk of collision between them is reduced. The formula of alignment, $\vec{a_i}(t)$ is expressed in (7), where m_a is the cardinality of the set A_i.

$$\vec{a_i}(t) = \left(\frac{1}{m_a} \sum_{\forall b_j \in A_i} \vec{v_j}(t) \right) - \vec{v_i}(t) \tag{7}$$

When each *boid* b_i applies the basic behaviors of cohesion $\vec{c_i}(t)$, separation $\vec{s_i}(t)$, and alignment $\vec{a_i}(t)$ in combination, as result the formation is held together and moves coordinately. The formula for flocking, $\vec{fk_i}(t)$ is expressed in (8).

$$\vec{fk_i}(t) = \alpha \vec{c_i}(t) + \beta \vec{s_i}(t) + \delta \vec{a_i}(t) \tag{8}$$

Where each behavior is multiplied by the weights α, β, and δ and the range of values of these weights is $[0, \infty)$. The net force is determined by the force $\vec{fk}_i(t)$ and limited by the maximum force f_m.

$$\vec{F_i}(t) = \begin{cases} f_m \frac{\vec{fk_i}(t)}{\left\| \vec{fk_i}(t) \right\|} & \text{if } \left\| \vec{fk_i}(t) \right\| > f_m \\ \vec{fk_i}(t) & \text{otherwise} \end{cases} \tag{9}$$

Acceleration is equal to net force divided by the mass of the *boid* and is expressed in (10)

$$\vec{ac_i}(t) = \frac{1}{m_b} \vec{F_i}(t) \tag{10}$$

The new position of *boid* b_i at time t is calculated from its velocity $\vec{v_i}(t)$ and its previous position at time $t - \Delta t$, as presented in formulas (11) and (12).

$$\vec{v_i}(t) = \begin{cases} r_m \frac{\vec{v_i}(t-\Delta t) + a\vec{c}_i(t)}{\|\vec{v_i}(t-\Delta t) + a\vec{c}_i(t)\|} & \text{if } \|\vec{v_i}(t - \Delta t) + a\vec{c}_i(t)\| > s_m \\ \vec{v_i}(t - \Delta t) + a\vec{c}_i(t) & \text{otherwise} \end{cases} \tag{11}$$

$$\vec{p_i}(t) = \vec{p_i}(t - \Delta t) + \vec{v_i}(t) \tag{12}$$

In addition, it is necessary to limit the magnitude of change in orientation of the *boids* to prevent that *boids* look nervous due to abrupt changes and apply a behavior to avoid the walls. For the sake of space, the details of the implementation of these features is available online in the project code based on the library OpenSteer (`https://github.com/Zapotecatl/MetricsBoids`).

Performance Metrics

In this work the performance of the *boids* was evaluated in terms of extension, polarization and frequency of collision (Huth and Wissel, 1992)(Zheng et al., 2005) as quantitative indicators to characterize a formation, these metrics are revisited and extended. In this work we propose the metrics of consistency in extension, consistency in polarization, and quality, all of them are quantitative performance metrics about the collective dynamics of a formation.

The extension reflects the degree of cohesion of the flock and is determined by the average distance between one *boid* and the center of the flock. In this work the extension is given in terms of centimeters. The minimum value of the extension is $0cm$, a value that represents the situation where all *boids* are gathered together in one point in the environment. The maximum value of the extension depends on the shape and size of the pond, the number of *boids* and their distribution in the pond. The center of the flock, a value required to calculate its extension, is denoted as $cen(t)$, and it is expressed in (13).

$$c\vec{e}n(t) = \frac{1}{n} \sum_{i=1}^{n} \vec{p_i}(t) \tag{13}$$

The extension of the flock at time t is denoted as $ext(t)$ and it is calculated by applying (14).

$$ext(t) = \frac{1}{n} \sum_{i=1}^{n} \|c\vec{e}n(t) - \vec{p_i}(t)\| \tag{14}$$

The polarization is defined as the average of the angular deviation of each *boid* with respect to the average orientation of the entire group and expresses the degree of alignment of the *boids* headings, if *boid* belonging to the flock are oriented in similar directions a flock has a small polarization. Polarization holds a value in the range $[0°, 90°]$, where $0°$ represents a flock with an optimal parallel orientation where *boids* are perfectly aligned, and $90°$ represents a flock with the highest degree of "confusion"where *boids* are

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

completely unaligned. The average orientation of the group is denoted as $\vec{\mu}_p(t)$ and it is expressed in (15).

$$\vec{\mu}_p(t) = \frac{1}{n}\sum_{i=1}^{n} \vec{f}_i(t) \tag{15}$$

The angle between the vectors $\vec{f}_i(t)$ and $\vec{\mu_p}(t)$ is represented by the symbol $\angle$ and expressed in (16), and the polarization of the flock at time t is denoted as $pol(t)$ and it is calculated from the values obtained in (16) as expressed in formula (17).

$$\angle(\vec{f}_i(t), \vec{\mu}_p(t)) = \frac{180}{\pi} \arccos\left(\vec{f}_i(t) \cdot \left[\frac{\vec{\mu}_p(t)}{\|\vec{\mu}_p(t)\|}\right]\right) \tag{16}$$

$$pol(t) = \frac{1}{n}\sum_{i=1}^{n} \angle(\vec{f}_i(t), \vec{\mu}_p(t)) \tag{17}$$

The frequency of collision represents the degree of conflict among *boids* and is defined as the average of the number of *boids* in the collision state. The frequency of collision holds a value in the range $[0, 1]$, where 0 represents the ideal scenario where no collision occurs, whereas 1 represents the worst scenario where all agents collide with each other. When a *boid* b_i is in the collision state, the value of $c_i(t)$ is 1, otherwise its value is 0. The formula to calculate the collision state of *boid* b_i is expressed in (18), where r_b is the radius of the body of the $boid$.

$$c_i(t) = \begin{cases} 1 & \text{if } \|\vec{p}_j - \vec{p}_i\| < r_b, j = 1, ..., n, i \neq j \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

The number of *boid* in collision state is expressed in (19).

$$col(t) = \sum_{i=1}^{n} c_i(t) \tag{19}$$

The frequency of collision of the flock at time t is denoted $fcol(t)$, as expressed in (20).

$$fcol(t) = \frac{1}{n} col(t) \tag{20}$$

Proposed Metrics

In order to capture the global performance of a flock considering the different aspects of its behavior that are represented by the combination of previous metrics, we propose three new metrics: 1) consistency in the extension, 2) consistency in the polarization, and 3) quality. These metrics express the relationship between the extension, polarization and the frequency of collision.

The **consistency in extension** aims at balancing the radius separation in a formation. Minimizing the values of extension and frequency of collision affects the flock since the cohesion of groups is maintained by the combination of these metrics. The extension of a flock decreases when *boids* get close to each other, which is considered a positive action. However, if they get to close to each other, collisions might happen, which is considered a negative action. Therefore a careful balance of these metrics is necessary. The consistency in the extension evaluated at time t is denoted as $cns_{exp}(t)$ and it is expressed in (21).

$$cns_{ext}(t) = 1 - \frac{\sum_{i=1}^{m} \|c\vec{en}(t) - \vec{p_i}(t)\| + k \cdot col(t)}{max_e \cdot n} \tag{21}$$

where k is a distance penalty that holds a value in the range $[0, max_e]$ and m to denote the number of *boids* that do not collide with each other. The constant max_e represents the maximum extension that depends on the shape and size of the pond, the number of *boids* and their distribution in the pond. In this work we consider the value of max_e as half of the distance between two extreme points of the pond, which normalizes the second term in (21). Finally the complement is calculated. The consistency in the extension holds a value in the range $[0, 1]$, where 0 indicates the worst consistency and 1 the optimum consistency.

Expression (21) captures the necessary balance between the radius separating *boids* and the frequency of collision. Each *boid* adds a proportional contribution of its distance towards the center of the flock to the group consistency. However if the *boid* collides this contribution is overridden and summarized as a constant in the penalties.

if $k = max_e$ the integrity of the *boids* is highly weighted. A flock is evaluated with a value of $cns_{exp} = 0$ in a situation where all its members collide, whereas consistency in extension it approached to 1 when *boids* not collide. On the other hand, $cns_{exp} = 1$ can only be achieved if $k = 0$ and all the members of flock collide.

The **consistency in polarization** aims at balancing the orientation of a flock. Minimizing the values of polarization and frequency of collision affects the flock since the *boids*' goal is to achieve coordinated motion of uniformly aligned *boids* that do not collide to each other. The polarization of a flock decreases when *boids* are similarly oriented, which is considered a positive action when moving together. However the *boids* may need to change their orientation, but if such a change is not performed promptly *boids* may collide with each other. Therefore a careful balance of these measures is necessary. The consistency in the polarization evaluated at time t is denoted as $cns_{pol}(t)$ and it is expressed in (22).

$$cns_{pol}(t) = 1 - \frac{\sum_{i=1}^{m} \angle(\vec{f}_i(t), \vec{\mu}_p(t)) + \rho \cdot col(t)}{180 \cdot n} \tag{22}$$

where ρ is an angle penalty that holds a value in the range $[0°, 180°]$ and m to denote the number of *boids* that do not

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

collide with each other. The constant $180°$ represents the maximum polarization, which normalizes the second term in (22). Finally the complement is calculated. The consistency in the polarization holds a value in the range of $[0, 1]$, where 0 indicates the worst consistency and 1 the optimum consistency.

Expression (22) reflects, on its side, the necessary balance between the angular orientation of the *boids* and the frequency of collision.

Each *boid* adds a proportional contribution of its angular deviation with respect to the average group orientation. Similar to the consistency in extension, if the *boid* collides this contribution is overridden and summarized as a constant in the penalties to obtain the consistency in polarization.

Again, in this measure if $\rho = 180°$ the integrity of the *boids* is highly weighted. A value of $cns_{pol} = 0$ is achieved when the group is highly polarized and all its members collide. On the other hand, $cns_{pol} = 1$ when the group is perfectly aligned.

The **quality** aims at establishing a criterion to combine the results in the consistency in both extension and polarization, in such a way that we can evaluate the global performance of a flock. The quality is weighted by the factors σ and γ which determine, respectively, the influence of consistency in the extension and polarization on the final result. The quality is expressed in (23).

$$qlty(t) = \sigma \cdot cns_{ext}(t) + \gamma \cdot cns_{pol}(t) \tag{23}$$

where $0 \leq \sigma \leq 1$, $0 \leq \gamma \leq 1$ and $\sigma + \gamma = 1$

Note that for each one of the previous metrics, both the punctual metric during the simulation steps, as well as the resulting metric in one simulation run are calculated. The later is calculated as the average of the corresponding measure during the simulation steps. For instance, the **total quality** is expressed in (24).

$$qlty = \frac{1}{l} \sum_{t=1}^{l} qlty(t) \tag{24}$$

where the number of iterations performed during the simulation is denoted by l.

Results

The *boids* model was implemented and run on a computer with i5 processor and 16 GB of RAM equipped with a Nvidia Geforce GT 730 graphics board under Linux. The Open Source 3D Graphics Engine (OGRE) was used and an object-oriented programming approach was applied for our experiments. The library OpenSteer enabled us an accurate replication of *boids* to conduct experiments on fair and common basis (Reynolds, 1999), the source code of this project is available online (`https://github.com/Zapotecatl/MetricsBoids`).

The shape of the pond that we used in our simulations is a cuboid with dimensions in width, height and depth, denoted as W, H and D, respectively (see Figure 2). The *boids* were separately, initially distributed in random positions where the maximum distance that separates a *boid* from the central point of the pond is $50cm$, in such a way that they can be perceived by each other. The *boids* avoid colliding with the walls of the pond so periodic boundary conditions are not applied.

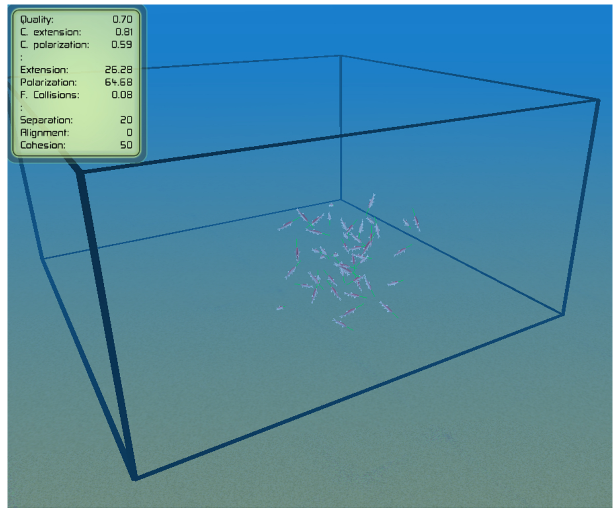

Figure 2: The shape of the pond used in our simulations is a cuboid. The *boids* can collide with the walls of the pond so periodic boundary conditions are not applied.

The 3D environment allows qualitatively visualize the result of our metrics (see Figure 3). The videos on how the groups look in relation to metrics are available online (`https://vimeo.com/user49682258/videos`).

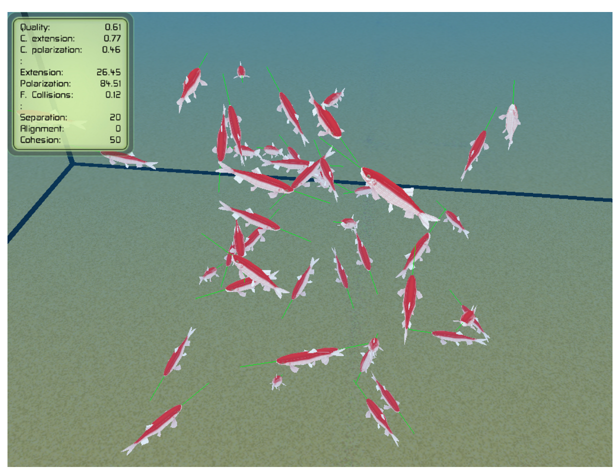

Figure 3: The figure shows a flock evaluated by the quality metric with a value of 0.61.

Extensive experiments were conducted to evaluate in

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

terms of previous metrics the performance of *boids* model. The experiments consisted in varying the radii r_s and r_a that determines the area of perception associated with the behaviors of separation and alignment in order to estimate the performance of the flocks under different configurations. Cohesion radius $r_c = 50cm$ for all experiments. For each experiment configuration the simulation was repeated 15 times for obtaining representative averages. The parameters used in our simulation are shown in the table 1.

Parameter	**Value**	**Description**
W	*300cm*	*Size of pond in width*
H	*150cm*	*Size of pond in height*
D	*300cm*	*Size of pond in depth*
l	*100000*	*Number of iterations*
n	*50*	*Number of boids*
r_b	*5cm*	*Radius of the body*
f_m	*50cm/s*	*Maximum force*
s_m	*25cm/s*	*Maximum speed*
m_b	1	*Mass*
r_c	50cm	*Cohesion radius*
r_s	*(0-50)cm*	*Separation radius*
r_a	*(0-50)cm*	*Alignment radius*
θ_c	*360°*	*Cohesion field of view*
θ_s	*360°*	*Separation field of view*
θ_a	*360°*	*Alignment field of view*
α	*25*	*Cohesion weight*
β	*25*	*Separation weight*
δ	*25*	*Alignment weight*
k	225cm	*Penalty distance*
ρ	180°	*Penalty angle*
σ	0.5	*C. extension weight*
γ	0.5	*C. polarization weight*

Table 1: Parameters used in our simulation with the *boids* model.

Figure 4 shows that the shorter the radius of separation and bigger the radius of alignment decreases the total extension. That is explained by the fact that, as long as the alignment radius is increased, the *boids* are motivated to establish the formation.

Figure 5 shows that when *boids* are assigned a big radius of alignment the total polarization is small. That is explained by the fact that, as long as the alignment radius is increased, the *boids* are motivated to go in the same direction.

Figure 6 shows that the bigger the separation radius, the smaller the total frequency of collision. That is explained by the fact that the *boids* are usually dispersed when they apply a big separation radius and for that the possibility of collision is reduced.

It is worth recalling that the quality metric provides a value that combines the results of the consistency in the extension and consistency in the polarization previously introduced. Figure 7 shows that the maximum value of total quality is in the order of $\cong 0.93$ resulting from different configurations with which we can conclude that, If the integrity of the members of the flock is highly weighted, the flock is evaluated with a **good quality under these scenarios**: (1)

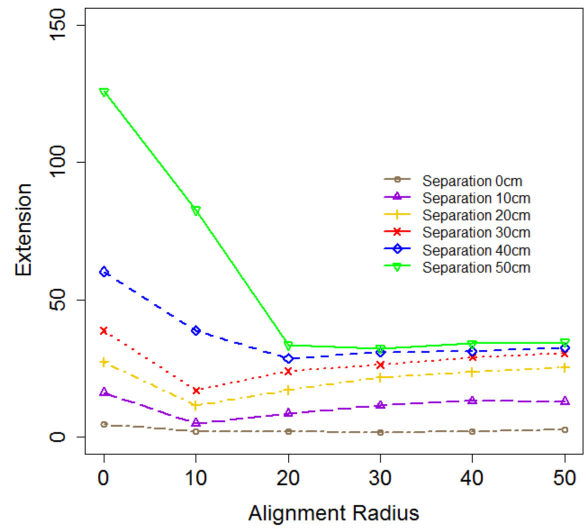

Figure 4: Extension, the minimum value of total extension is in the order of $1.64cm$ with $r_c = 50cm$, $r_s = 0cm$, and $r_a = 30cm$.

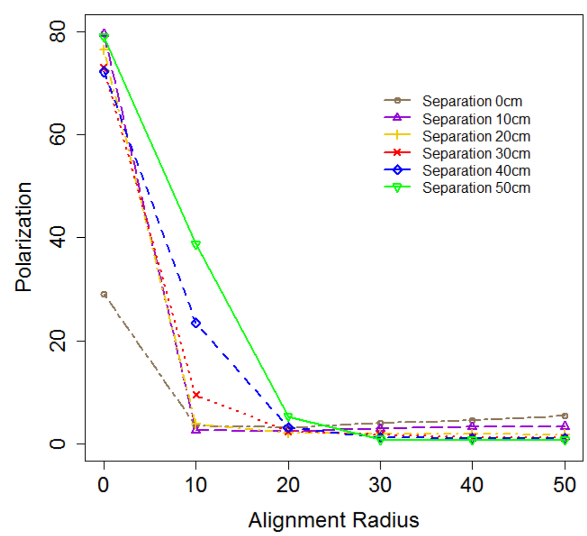

Figure 5: Polarization, the minimum value of total polarization is in the order of $0.79°$ with $r_c = 50cm$, $r_s = 50cm$, and $r_a = 50cm$.

The value of the separation radius is in a range that enables collision avoidance. This radius is in the range $[20, 50]$, (2) The value of the alignment radius is greater than or equal to the radius of separation, and (3) The value of the alignment radius is less than or equal to the radius of cohesion, as illustrated in Figure 7.

Figure 8 shows a configuration of radii of perception r_c,

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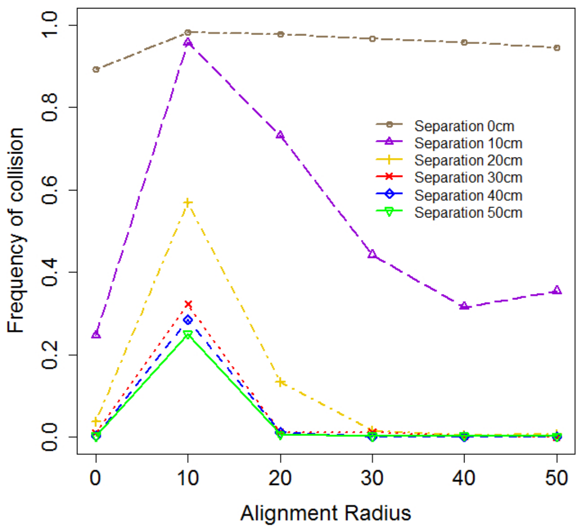

Figure 6: Frequency of collision, the minimum value of total frequency of collision is in the order of 0.0001 with $r_c = 50cm$, $r_s = 50cm$, and $r_a = 50cm$.

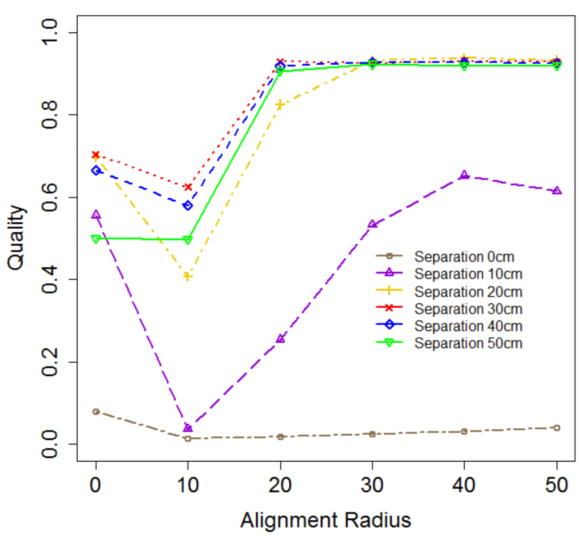

Figure 7: Quality, the maximum value of total quality is in the order of $\cong 0.93$ resulting from different configurations.

r_s and r_a of the flock that received the highest evaluation based on the quality metric.

Based on previous results we confirm that the combined application of the behaviors of cohesion and separation contribute to keep the flocking *boids* gathered without colliding. The alignment behavior on its side is useful to achieve coordinated motion of the *boids* and also avoid collisions.

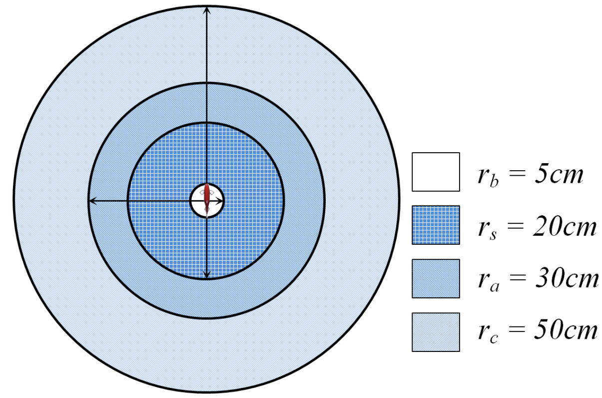

Figure 8: A configuration of areas of perception that received the highest evaluation based on the quality measure are: $r_c = 50cm$, $r_s = 20cm$ and $r_a = 30cm$.

The tune of values for the achievement of coordinated flocks is far from being trivial, because the parameters that influence the behaviors of the *boids* are closely interrelated. A small separation radius, for instance, brings *boids* to gather in compressed and "well-welded"groups, that are however quite prone to collide among them. In contrast, a big separation radius results in *boids* that are comfortably separated from each other and which are more prone to detaching from the flock.

Concluding Remarks and Future Work

The proposed metrics represent in such a way the dynamics of the system and they contribute to the analysis of the phenomenon of collective coordinated motion, in terms of generic global parameters and the relationships among these parameters. Therefore, since a flock refers to a group that shows a class of polarized, non-colliding and aggregate motion (Reynolds, 1987), the metrics allow to establish a general benchmark for the evaluation of models of the type flock; not only for *boids* model.

The performance metrics proposed in this research might be applied not only for qualifying some aspects of group behavior but also for tuning the behavior of groups of artificial agents. In effect, parameters such as radius of perception, field of view, and weight of behaviors for producing flocks able to reach the highest quality can be certainly estimated. Therefore, the metrics proposed in this work can be used for the design of flocks.

For example, is possible to apply a methodology that uses genetic algorithms for evolutionary development of a flock (Wood and Ackland, 2007; Olson et al., 2013). The fitness function apply quality metrics to punish flocks where members collide too and reward flocks where members do not collide. Resulting in the optimization of the behavior of agents so that they form flock and simultaneously not collide. The parameters to deliver the optimal results can be

DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054

applied in a animated flock or in autonomous flying robot (Virgh et al., 2014).

As future work, we are also working on the refinement of performance metrics that enable a more representative evaluation of the dynamics of the flock than current metrics. Note, for instance, that using current metrics a flock can be evaluated similarly when *boids* are fully dispersed that when they form dispersed subgroups in the environment. These situations should be properly identified.

Acknowledgements

We gratefully acknowledge the facilities provided by INAOE and IIMAS. Jorge L. Zapotecatl was supported by the scholarship 13139 of CONACyT, México. We are grateful to two anonymous reviewers who provided useful comments.

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DOI: http://dx.doi.org/10.7551/ 978-0-262-33936-0-ch054