Physica A 507 (2018) 289–293

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

The milling pattern in animal groups and its dependence on the density and on the number of particles

Dorilson S. Cambui [a,b,*], Edmilton Gusken [b], Marfa Roehrs [b], Tarras Iliass [c]

[a] Secretaria de Estado de Educação de Mato Grosso, Cuiabá, Mato Grosso, Brazil
[b] Universidade do Estado de Mato Grosso, UNEMAT, Departamento de Matemática, Barra do Bugres, Mato Grosso, Brazil
[c] Laboratoire de Physique de la Matière Condensée Faculté des Sciences Ben M'Sik, Casablanca, B.P.7955, Morocco

HIGHLIGHTS

- We model self-propelled particles system used to study the live organisms motion.
- Important parameters in this system are speed, density and the number of particles.
- We explore the interplay between speed, density, and number of particles.
- Guided by the recent investigations, agents follow rules based in animal behavior.
- We find that such parameters influence the milling formation.

ARTICLE INFO

Article history:
Received 6 April 2018
Available online 16 May 2018

Keywords:
Biological systems
Collective motion
Self-propelled particles
Animal behavior
Collective behavior rules

ABSTRACT

Moving animal groups often exhibit aggregation behavior. In many species, the collective behavior invariably depends on local interactions among individuals. In such groups, the mechanism of group formation require that interaction rules be followed by all members, and as consequence, animal aggregates such as schools of fish, flocks of birds, and swarms of locusts exhibit a variety of dynamical behavior patterns. In this paper we investigated only the milling pattern. Of particular interest to us is to analyze its dependence on the density and on the number of particles. We found that the milling formation depends of these two physical quantities.

1. Introduction

The subject matter of this paper concerns collective behavior of animals which exhibit a tendency to live in groups with coordinated motions [1]. The biological reasons for group living are, among others, to increase protection against predators, to follow better migration routes, and to enhance food finding. These benefits are assumed to increase with increasing group size [2]. Examples of biological aggregations are groups of organisms such as fish schools, bird flocks, insect swarms, and mammal herds [3–6]. Many studies have been inspired by animal behavior phenomena. Based on the biological laws of collective motion, computer simulation models (individual based) have been able to reproduce multiple collective patterns within certain parameter ranges [7–16]. Effects of the speed on the collective behavior also have been investigated [17,18]. From biological inspiration, these models predict that individuals follow certain behavioral rules, where each individual may have, depending on distance, three interaction zones around himself: repulsion, alignment and attraction. Generally,

* Corresponding author.
E-mail address: dcambui@fisica.ufmt.br (D.S. Cambui).

https://doi.org/10.1016/j.physa.2018.05.111
0378-4371/

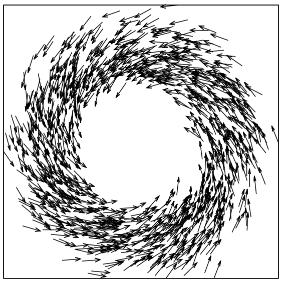

Fig. 1. Milling behavior.

attraction is considered to act on long ranges, alignment on intermediate ranges, whereas repulsion acts on short ranges. In this our study, we consider only interactions type attraction and velocities alignment.

In a wide range of biological systems, the process of formation and movement of animal groups is the result of the numerous interactions between individuals. This phenomena may give rise to a variety of animal collective patterns, generated by simple rules followed by the group members, the which have been observed and reported in various species in nature [19]. Some spectacular examples of group patterns are: swarming, milling, and polarized groups. The swarming pattern displays low directional alignment between neighboring individuals, in the milling pattern the group moves in round their center of mass, and the polarized pattern is one in which the individuals tend to be aligned with each other. The milling formation (see Fig. 1), where particles follow one another around an empty core, is observed in both two and three dimensions [6,19,20], in different sizes [1,21], and has been observed in army ants, insects, microorganisms, however more often in school of fish [19,22–24].

One of the aspects of animal groups is their variation in size, given by the number of individuals within the group. It is a key aspect because can have important effects on animal behavior patterns. For this reason, our objective in this current study is to explore the influence of the density on the milling formation. We examine the effect of the density and of the particles number on this behavior in a system composed by self propelled particles. Simulations were made in order to produce a milling pattern similar to those observed, for example, in schools of teleost fish, insects, and microorganisms [23–25].

In following of the paper, we present in Section 2 the model used in this contribution, in Section 3 we discuss its computational implementation, in Section 4 we present our results and in Section 5 we discuss their implications.

2. Definition of the model

We consider an extension to the self-propelled particle model presented in [10], where each particle i, is characterized by its position $\mathbf{x}_i(t)$ and velocity $\mathbf{v}_i(t)$ in a two-dimensional space, and at each step of discrete time ($\tau = 1$), the positions are updated according to,

$$\mathbf{r}_i(t+\tau) = \mathbf{r}_i(t) + \mathbf{v}_i(t)\tau. \quad (1)$$

As previously mentioned, the model is composed of two interaction regions called of attraction zone (ATT) of radius r_a and orientation zone (ORI) of radius r_o, with N_a and N_o individuals respectively. Individuals interact with their neighbors within these zones, according to the distance d_{ij} between them. This behavior is modeled by changing the direction of the ith individual in according to,

$$\mathbf{d}_i^{(ORI)} = \frac{\sum_{j=1}^{N_o} \mathbf{v}_j}{\left|\sum_{j=1}^{N_o} \mathbf{v}_j\right|} \quad (2)$$

$$\mathbf{d}_i^{(ATT)} = \frac{\sum_{j\neq i}^{N_a} \mathbf{r}_{ij}}{\left|\sum_{j\neq i}^{N_a} \mathbf{r}_{ij}\right|}. \quad (3)$$

The vector $\mathbf{r}_{ij}$ is the unit vector pointing from individual i in the direction of neighbor j, and $\mathbf{r}_{ij} = \frac{(\mathbf{r}_j - \mathbf{r}_i)}{|\mathbf{r}_j - \mathbf{r}_i|}$. If only there are neighbors within the orientation zone, the individual i aligns and moves in the same direction of the group in according rule given by Eq. (2). For the case in that neighbors find itself only in the attraction zone, the Eq. (3) give us the interaction rule that updates the motion direction of the individual i. If neighbors are found in both orientation and interaction zones then the resulting direction is the average of $d_i^{(ATT)}$ and $d_i^{(ORI)}$, weighted by the number of individuals in the attraction and orientation zones, respectively. Following Vicsek [10], we added the noise term $\varepsilon\eta$ in the motion direction. ε is a random