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Guiding a Group of Locally Interacting Autonomous Mobile Agents

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Abstract: Consider a simple but typical distributed system of *n* autonomous agents. Each agent moves with the same speed but with different headings which are updated by using a local rule based on the average of its own heading plus the headings of its neighbors. This model captures the major features of flocking behavior of birds. In this paper, we are trying to control the headings of a group of agents but do not (1) use centralized methods; (2) change the local rule of the existing agents in the system. A case study is to coordinate the headings of agents by adding one Shill agent. It is a natural way to intervene in the collective behavior of distributed systems, but different from the approach of distributed control. It may bring out many interesting issues and challenges on the control of complex systems.

Key words: Complex Systems, Collective behavior, BOID model, Shill Agent

1 Introduction

Flocking is a natural phenomenon found in birds, fishes and other animals [1, 2]. It is a kind of collective behavior which has been studied for many years. However, flocking of birds in airports is dangerous. How we drive them away? In this case, obviously we can not use centralized control, such as broadcasting the order to the birds to change to the desired flying direction. The current solution is to use cannon to shoot them. Are there better solutions? Can we guide birds' flight if we know how they fly, e.g., given a multi-agent model for birds, can we control the collective behavior of locally interacting autonomous agents?

So the core of this problem is '*Given the local rule of agents, how we control the overall collective behavior of the system?*' Very few people work on this kind of 'control' which ***does not (1) use centralized methods***, such as adjusting a global parameter; ***(2) change the basic local rule of the existing agents in the system***, because in some real applications, it is very difficult or even impossible to change the local rules of agents, such as the flying strategies of birds. Then, what is the feasible way to intervene in the collective behavior?

Since collective behavior is a kind of macroscopic feature of a multi-agent system, usually adding one or a few more agents will not affect it. But if those agents are special ones which can be controlled, even though only a small number (in some cases, only one), it can dramatically change the collective behavior as will be shown in Section 3. So in this paper, a way to control the system without changing the local rules of the existing agents is to add one (or a few) special agent which can be controlled. Therefore its behavior does not necessarily obey the local rules as the ordinary agents do. However, the existing agents still treat the special agent as an ordinary agent, so the special agent only affects the local area with limited power. The special agent is the only controlled part of the system and it indeed changes the collective behavior of the system by `cheating' and 'seducing' its neighboring ordinary agents. So we do not call the special agent a leader. Instead, we call it a ***Shill***.

This paper is going to study how a *shill* can be used to control the headings of a group of mobile agents demonstrated based on the simplified version of BOID [2] model proposed by Vicsek *et al* [1]. The current control theory cannot be applied directly to this *shill*-guiding approach because this is a nondestructive intervention in a locally interacting autonomous multi-agent system, which is not allowed to change the local rules of the existing agents. The *formation control* [3] mainly focuses on how to design the local rules of a team of robots to maintain a geometric configuration during movement, which is a very special kind of collective behavior. The *pinning control* [4] is especially for stabilizing dynamical networks (with special topology, such as random networks, small-world and scale-free networks) by imposing controllers on a small fraction of selected nodes in the network. No one appear to have directly studied the above mentioned *shill*-guiding problem in the literature. Recently, Jadbabie *et al* [5] investigated a multi-agent model which is slightly different from the one proposed by Vicsek *et al*, they showed that under some *a priori* connectivity conditions, the group will eventually move in a same direction even without centralized control. An idea in [5] worthy of mention is the *Leader-Following* model, which has a leader agent with fixed heading. But it did not tell how to implement synchronization by a leader.

The rest of this paper is organized as follows: our *shill-guiding* model based on the simplified BOID model is set up in Section 2. Some computer simulations and a rigorous case study are introduced in Section 3, which show that one *shill* is possible to control the collective behavior of the whole group. Conclusions are given in Section 4.

2 THE SHILL-GUIDING MODEL

In 1995, to investigate the emergence of self-ordered motion, Vicsek *at al.* [1] proposed a model which is actually a simplified version of BOID by only keeping the *Alignment* rule. There are *n* agents ($\boldsymbol{x}_i(\cdot)$, $\theta_i(\cdot)$) for *n* birds, labeled from *1* through *n*, all moving simultaneously in the two-dimensional space. The velocity of agent *i* at time *t* is defined by $\boldsymbol{v}_i(t) = (v\ cos(\theta_i(t)),\ v\ sin(\theta_i(t)))$ is constructed to have an absolute value *v* and a heading given by the angle $\theta_i(t)\in[0,2\pi)$. The position of agent *i* at time *t* is denoted as $\boldsymbol{x}_i(t)$. The neighborhood of agent *i* at time *t* is defined as $N_i(t) = \{j \mid \|\boldsymbol{x}_j(t)-\boldsymbol{x}_i(t)\| \le r,\ j = 1,2,\ldots,n\}$, where *r* is the radius of the neighborhood circle. For any agent *i*, its heading and position are updated by (1) and (2) below if ignoring the noise:

$$\theta_i(t+1) = \langle\theta_i(t)\rangle_r \quad (1)$$

$$\boldsymbol{x}_i(t+1) = \boldsymbol{x}_i(t) + \boldsymbol{v}_i(t+1) \quad (2)$$

where $\langle\theta_i(t)\rangle_r$ is the angle of the sum of the velocity vectors of neighbors of agent *i*: $\sum_{j\in N_i(t)}\boldsymbol{v}_j(t)$. It can be obtain by

$$arctan\ [\sum_{j\in N_i(t)}\sin(\theta_j(t)) / \sum_{j\in N_i(t)}\cos(\theta_j(t))] \quad (3)$$

with some necessary regulations reflecting angles of $[0,2\pi)$.

In order to guide headings of agents, one *shill* denoted as $\langle x_0, \theta_0\rangle$ is added into the system. The ordinary agents still keep the local rule (1) and (2) to update its position and heading. The only difference is the neighborhood $N_i(t)$ for agent *i* will consider the *shill*: $N_i(t) = \{j \mid \|x_j(t)-x_i(t)\| \le r,\ j = \mathbf{0},1,2,\ldots,n\}$. And the *shill* does not exactly obey the local rules as the ordinary agents do, its position and heading is decided by the control law $\boldsymbol{u}$:

$$\langle x_0, \theta_0\rangle_t = \boldsymbol{u}\ (x_1, \ldots, x_n, \theta_1, \ldots, \theta_n, t)$$

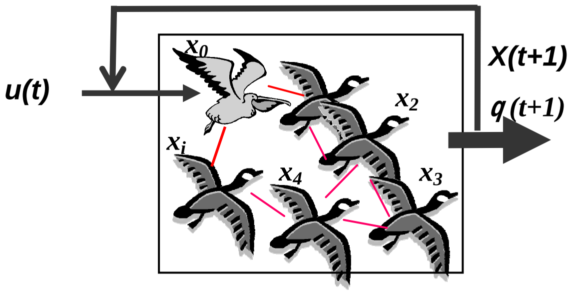

Figure 1. The framework for controlling bird flocking behavior by adding a *shill*. Two birds are linked if they are neighbors of each other at time *t*.

Note that $<x_{0,}\ \theta_0>$ may be subject to some constraints. For example, the constraint of $\boldsymbol{x_0}$(t+1) = $\boldsymbol{x_0}$ (t) + $\boldsymbol{v_0}$ (t) will make the *shill* behave like an ordinary agent except the way it decides its own heading. We call it a *powerful shill* if it can fly to anywhere with a deceptive heading. Obviously, the control law ***u*** is different for different purposes/tasks.

3 SIMULATIONS AND A CASE STUDY

There are many control problems should be considered: in what condition we can use the *shill* to control the system (the controllability problem); which kind of information we can use for control (the observation problem), e.g., the *shill* can only see some nearest agents but not all other agents; how can we control when the local rule is not clear (the learning and adaptation problem), etc. It will be one of our future projects. We do not intend to answer all these questions in this paper. As the beginning, we first want to show how a shill agent can control the collective behavior of the whole group by computer simulations and a rigorous case study for a simple task. Here we only consider the cases of: the *shill* is a *powerful Shill* and knows the details of the local rule about the ordinary agents; the *shill* can observe all information (headings and positions) of all ordinary agents at any time step.

3.2. Computer Simulations of Manual Control on the *Shill*

The simulation program (ControlBOID-3.5.exe in [6]) is made by Visual Basic. The *shill* can be controlled manually by keyboard and mouse. There are videos [6] about different control tasks:

Use a *shill* to synchronize and turn headings of the group (shill-synchronize-turn.avi);

Use a *shill* to keep the group connected or to dissolve a group (shill-connect-disslove.avi);

Use a *shill* to lead the group circling (shill-circle.avi).

Some cues can be obtained from the simulations: local effect will spread through the whole system; it is possible to synchronize, group, dissolve or turn agents by one *shill*; turning is an important task among others; the position of *shill* is important and subtle; keeping the group connected seems important in guiding the group movement; it seems to keep the *shill* on the edge of the group on opposite side is efficient while turning a group, etc.

3.1. A Case Study of the Control Law for the *Shill*

The *problem* we consider here is: for a group of n agents with initial heading of $\theta_i(0)\in[0, \pi)$, $1\le i \le n$, what is the control law for the *shill* so that all agents will move to the direction of π eventually?

Suppose the local rule about the ordinary agents is known. Suppose also that the position $\boldsymbol{x_0}(t)$ and heading θ_i(t) of the *shill* can be controlled at any time step *t*. Suppose further that the state information (headings and positions) of all ordinary agents are observable at any time step. Now we propose a control law u_β(see Fig. 2) which is defined as:

$$x_0(t) = x_{s(t)}(t) \tag{4}$$

$$\theta_0(t) = \begin{cases} \theta_{s(t)}(t)+\beta & \text{if } \theta_{s(t)}(t) \le \pi-\beta \\ \pi & \text{if } \theta_{s(t)}(t) > \pi-\beta \end{cases} \tag{5}$$

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where $\beta \in (0, \pi)$ is constant, and $s(t)$ is defined as the 'worst' agent of time step t: $\theta_{s(t)}(t) = \arg\min_{1\le i\le n}\{\theta_i(t)\}$.

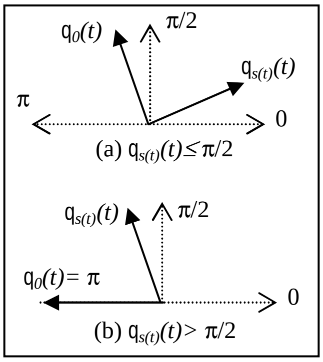


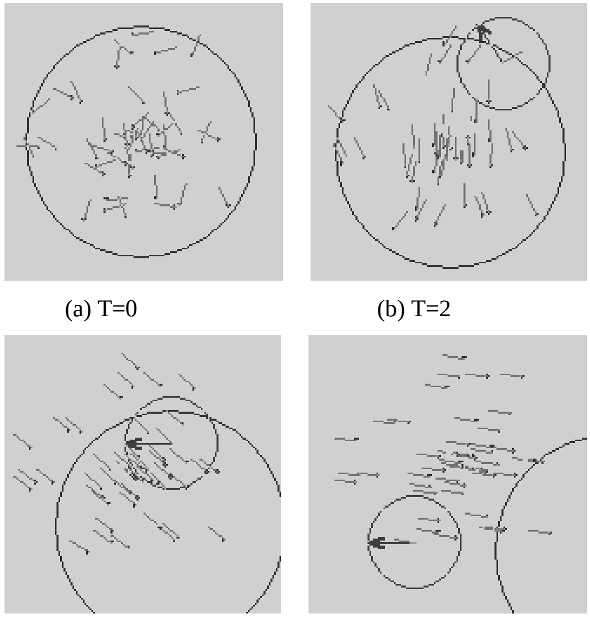
Figure 2. The control law u_β when $\beta = \pi/2$.

The intuition behinds u_β is to put the *shill* to the position of the `worst' agent $s$(t) at each time step t and try to `pull' it to the desired direction π. This greatly reduces the search space of positions and simplifies the control strategy. Note that we can not use $\theta_0=\pi$ for all the time because: (I) in the case where $\theta_{s(t)}(t)=0$ and the all the neighboring ordinary agents of the *shill* have headings of *zero* degree, the shill with $\theta_0=\pi$ can not change $\theta_{s(t)}(t)$ according to the update rule (1) ; (II) to avoid the ill-case where both of the numerator and denominator in (3) are *zero*. But in the final stages we do need $\theta_0=\pi$ to help the system to synchronize.

We have proved this control law u_β to be effective analytically: for any n>=2, r>=0, v>=0, and any initial headings and positions $\theta_i(0)\in[0, \pi)$, $\boldsymbol{x}_i(0)\in R^2$, $1\le i\le n$, the update rule (1) and (2) and the control law u_β will lead to the asymptotic synchronization of the group, i.e., $\lim_{t\to\infty}\theta_{s(t)}(t)=\pi$.

The snapshots of the relating computer simulation are showed in Figure 3. The video (control-upi-n50.avi) and the simulation program (ControlBOID-3.5.exe) can be downloaded from [6].

Although the case study is a very simple starting point, it shows that it is possible to change the collective behavior (headings) of a group by a *Shill*.



(a) T=0 (b) T=2

(c) T=45 (d) T=131

Figure 3. A simulation for a group of n=50 and $\beta=\pi/2$. The ordinary agents are represented by the small black dots with the line point to the direction they are moving. The *shill* is the one with arrow showing its heading direction. The circle of the *shill* shows the current neighborhood radius of all agents, and also indicates the effective area of the *shill*. The system starts from a random initialization (a). (b), (c) and (d) show the process. In (d), $\Delta\to 0$.

5 CONCLUSIONS

How we intervene in the collective behavior of a distributed system without changing the local rule of the existing agents is an important issue for complex systems but has not been well recognized yet. As an initial attempt to tackle this issue, we proposed a *shill-guiding* model in this paper. We have restricted ourselves on the study of the modified Boid model which does catch certain key properties of many real world complex systems (see, e.g., [1][2][5]). We add a *shill* in the distributed system and design the control law for the *shill* carefully for the control purpose. Although the *shill* doesn't behave as same as the ordinal agents, it is not recognized by the ordinary agents and is still treated as an ordinary agent. So the system is still distributed. But it works well as we have shown in the case study.

This *shill-guiding* approach is different from the *distributed control*. Indeed, we call it *soft control*. Both *soft control* and *distributed control* concern the macroscopic collective behavior (such as synchronization) of the self-organized multi-agent system with local rules. But every agent is treated as a control system and has its control law (which is the local rules) in *distributed control*; while in our framework, all these agents are treated as one system and the control law is for the shill only. *Soft control* can be regarded as a way of intervention to the distributed systems. With the growing literature of complex systems, the challenge of controlling complex systems becomes a key problem for both control scientists and many others.

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