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Dynamic coordinated control laws in multiple agent models

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Abstract

We present an active control scheme of a kinetic model of swarming. It has been shown previously that the global control scheme for the model, presented in [Systems Control Lett. 52 (2004) 25], gives rise to spontaneous collective organization of agents into a unified coherent swarm, via steering controls and utilizing long-range attractive and short-range repulsive interactions. We extend these results by presenting control laws whereby a single swarm is broken into independently functioning subswarm clusters. The transition between one coordinated swarm and multiple clustered subswarms is managed simply with a homotopy parameter. Additionally, we present as an alternate formulation, a local control law for the same model, which implements dynamic barrier avoidance behavior, and in which swarm coherence emerges spontaneously.

Keywords: Swarming; Control; Dynamics; Emergent behavior

1. Introduction

Multiple agent systems are comprised of a multitude of simple autonomous vehicles, which are loosely coupled via communication in order to achieve some desired goal. It is anticipated that such systems will play a key role in future deployments, as the drive to miniaturize electronic devices results in smaller and more capable self-mobile machines with limited decision making abilities. Thus, one of the main research areas of interest is the dynamic pattern formation and control of a large number of agents [2]. In particular, given a specific dynamical system composed of a large number of individual vehicles, each with specified limited decision-making and communication abilities, a vital question is under what conditions large-scale aggregate dynamics may be controlled to form coherent structures, or patterns. An example from electronics is a concept paper [3] which shows that complex patterns can arise from a large array of micro actuators interconnected to mimic a finite difference approxi-

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mation of standard reaction–diffusion partial differential equations (PDE). However, it is a static theory based on quite standard pattern formation theories from reaction–diffusion which assumes pure local coupling.

In contrast, many biological examples of coherent dynamical motion (swarming) exist in nature. Populations such as bees, locusts, and wolves often move in coordinated but localized efforts toward a particular target. In addition many more examples abound of populations of individuals that move according to local rules, and whose aggregate dynamics achieve an overall large-scale complex pattern or state. Bacterial colonies, which evolve in part via chemotactic response, are such an example. The mathematical biology community has been exploring models for animal swarms, and this work pinpoints some of the difficulties (see the survey paper [4]). Traditional models for biology populations involve local PDE for the population density [5]. Edelstein-Keshet et al. [6] recently considered such a model in one space dimension for African migratory locusts. These insects have a gregarious phase in which swarms of individuals can travel for days over thousands of miles. Evidence exists that the swarms remain cohesive even in the absence of a nutrient gradient. The analysis of [6] shows that such cohesive swarms cannot be described by traveling wave solutions of their one-dimensional advection–diffusion model. More recently, Mogilner and Edelstein-Keshet consider nonlocal interactions, in which the drift velocity of the population is determined by a convolution operator with the entire population [7]. These models, resulting in integro-differential equations, do sometimes produce coherent band-like structure. Earlier work by Edelstein-Keshet and Watmough [8] on army ant swarms, considers a one-dimensional model and shows the existence of traveling wave solutions for the leading edge of the pack, but they do not consider band-like solutions that would describe something like a locust swarm. These particular examples involve one-dimensional models and simulations. In summary, most studies of biological swarming involve models from continuum theory, many of which are based on some form of local communication, which are modeled by way of interactions or couplings.

The statistical physics community has recently tried to understand similar problems in situations where the number of individuals are very large. Statistical information derived for large numbers is less relevant to formations involving smaller numbers of individuals. However, the connection between the discrete and the continuous is an important problem that is well-studied in this field. The particle approach involves starting with simple rules of motion, involving combinations of biased random walks, sampling of motions and positions of nearby neighbors, with some governing strategy designed to mimic core components of animal interactions. For example, Schweitzer et al. [9] consider a theory of canonical-dissipative systems and the energetic conditions for swarming. Grünbaum [10] has derived advection–diffusion equations for internal state-mediated biased random walks. Mogilner and Edelstein-Keshet [11] consider both continuum and cellular automata models for populations of self-aligning objects. Stöcker [12] considers a hexagonally based cellular automata model for tuna school formation. These are just a few examples. In all cases, the local rules are precisely defined and aggregate motion can be observed in numerical simulations.

As an alternative to understanding coherent swarm structures that use finite models (noncontinuum theories), a recent body of work considers general particle-based models for self-propelled organisms (see, for example, [13–16]). Collective motion and swarming is observed along with interesting aspects of dynamic phase transitions, including crystalline like motion, liquid, solid, and gas-like states. Toner and Tu [17–19] use renormalization group ideas to study flocking motion in a particle-based model. Some of this work parallels classical statistical theory of transport which derives hydrodynamic equations from local interaction models [20–22]. The approach considered by Chang, et al. [23] considers agents in a scalar potential field and utilizes gyroscopic and braking forces.

In most cases presented, the agents are self-propelled and the nature of the coupling or communication imposes a given pattern. Here we consider similar aspects, but with the idea of controlling the communication to form patterns. In this Letter we consider kinetic models in which, depending on the control law used, the self-propelled agents communicate, either locally within a specified radius about each agent, or globally with every other agent in the swarm. Under appropriate choices of gyroscopic control laws, coherent motion of agents is observed. In general, the