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A collective motion algorithm for tracking time-dependent boundaries

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Abstract

We present a numerical method that allows a formation of communicating agents to target the boundary of a time-dependent concentration by following a time-dependent concentration gradient. The algorithm motivated by [3,1], allows the agents to move in space in a non-stationary environment. Our method is applicable to finding the boundary of any regular surface and may be of interest for studying motions of swarms in biology, as well as to engineering applications where boundary detection is an issue.
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Keywords: SWARMS; Collective motion; Agents; Control; Nonlinear dynamics

1. Introduction

We propose and study a method for a multi-agent system of autonomous vehicles to perform the exploration of a non-stationary environment. The goal of this exploration is to reach a designated target geometry, typically a boundary, and to describe that boundary. The current paper relates to the general objective of studying motions of swarms, which we understand as a collection of autonomous entities which rely on local sensing and simple behavior, interacting in a way that a more complex behavior of the whole group emerges from local interactions [13]. This type of behavior is well-known in natural phenomena, such as schools of fish [13] and colonies of insects [6]. One can find in the literature various

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other methods of simulating motions of distributed systems inspired by biology [6,11], and by economics-based concepts [15]. The applications of such motions are quite broad since substituting agents for humans is desirable in many areas, such as de-mining operations [14], mapping and exploration [2], navigation control [4], formation flying [12] and military planning [13].

The algorithm presented here models a group of agents to move on a given surface or within a prescribed volume, find its boundary and track it, while communicating with each other and spreading simultaneously over the surface. The environment in which the motion takes place varies in time. Such a method may provide insight to a better understanding of motions of swarms in biology [6]. The motion of swarms in military applications has been considered in recent years [13], since it offers an unmanned, dependable, flexible, self-organized type of network to achieve various military objectives, while replacing the burden of comprehensive communication, since the swarms interact primarily with their neighbors.

The particular goal of identifying and tracking the boundary of a surface which we address here, is analogous to the problem encountered in image segmentation of tracing the boundary of an object. Tracking contours as a function of time has been addressed in the pioneer work of Kass [9], in relation to localizing features in an image. Here we add more complexity to the situation in [9] since the motion of the agents starts far away from the boundary. Moreover, once the boundary is located the contour of agents moves along that boundary rather than keeping a fixed location.

The idea of adapting image processing techniques to simulate motions of swarms was proposed in [1], where the image segmentation technique of locating a contour with a model known as a snake [9], or energy-minimizing curve [7] is adopted. We extent that analogy by allowing the formation of agents to move on a time-dependent surface or on a surface whose boundary travels in time. In the current work, we explore the problem of simulating the motion of agents which effectively locate and follow the boundary of a surface of interest, assuming that the boundary is known to each agent and it is moving in time possibly along with the entire surface. The motion of agents takes place in either 2D or 3D.

The idea of the algorithm we present is to model the group of agents as a contour that deforms towards the boundary of the object. Interactions between nearby agents are assumed, the modeling of these interactions being analogous to having forces acting between nearby particles as in an elastic band. An energy functional results from this physical model in a continuum limit. The desired motion of the agents is obtained by minimizing this functional to which an appropriate goal dynamics term is added, so that its minimum is obtained as the agents land on the proposed target.

The algorithm assumes that each agent has the position of the boundary, has information on nearby agents, and evaluates its position on the surface as well as the local gradient of that surface. The movement of each agent can be modeled by a partial differential equation for the velocity of each vehicle. By discretizing this equation, we derive a numerical scheme for the motion of each agent. Each equation contains a term accounting for movement along the steepest descent on the surface and a term corresponding to movement parallel to the tangent to the boundary that is being tracked. Coordinated behavior is created by imposing local interaction rules among agents. These terms also dictate the manner in which the formation will converge towards the desired goal.

The paper is organized as follows. In the next section, we present an algorithm for an individual agent to accomplish the desired task. Then we continue in Section 3 with adding a sparsing term which connects the motions of nearby swarmers and prevents collisions of agents in real applications. Obtaining collective motion local communication rules is essential. Typically these rules determine a general pattern of significance in applications [13]. Consequently in Section 3 we present a PDE model that includes interaction