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Autonomous mobile bionanosensor networks for target tracking: A two-dimensional model

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ABSTRACT

This paper designs and models autonomous mobile bionanosensor networks for target tracking. In the bionanosensor networks considered in this paper, nano-to-micro scale bionanosensors autonomously coordinate their movement through the use of two types of signaling molecules: attractants to recruit bionanosensors to a location in the environment, and repellents to spread bionanosensors from a location over the environment. A mathematical model of autonomous mobile bionanosensor networks is first developed for target tracking in a two-dimensional area. Numerical results are then presented to discuss the impact of attractants and repellents on target tracking performance, providing an insight into how bionanosensors may be designed and engineered to improve the target tracking performance.

1. Introduction

In the emerging bionanosensor networks, nano-to-micro scale biological sensor and actuator devices, referred to as *bionanosensors* in this paper, are interconnected via molecular communication to perform various tasks in a cellular environment (e.g., the internal space of the human body) [1–5]. Bionanosensors are made of biomaterials and are capable of sensing and processing molecules in the environment. Examples of bionanosensors include synthetic molecular complexes [6], artificial cells [7] and genetically engineered cells [8].

In this paper, we design and model autonomous mobile bionanosensor networks for target tracking [9–11]. An autonomous mobile bionanosensor network considered in this paper consists of a group of bionanosensors capable of moving in the environment, releasing molecules to form a concentration gradient in the environment, and adjusting the direction of movement based on the concentration gradient. Targets are static or mobile objects that exist in the environment, and their presence is assumed to be a potential threat to the environment. The primary concern of the mobile bionanosensor network is therefore to coordinate their movement, identify the locations of targets, and continuously monitor the locations of targets if they move.

Target tracking is one of the "killer" applications in Wireless Sensor Networks (WSNs) [12]. In most cases, a statically deployed sensor network is used for target tracking. In [13], static sensors are hierarchically organized and information about the presence of targets is relayed from sensors that detect targets to other sensors in the hierarchy and to the root node. In [14,15], sensors deployed statistically are reconfigured dynamically to track moving targets. A limited number of works have investigated the use of mobile sensors for target tracking. In [16,17], for example, distributed mobility management schemes are proposed for mobile sensors to autonomously determine

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where to move to better track a moving target. In [18], a mobile sensor is directed by the mobile sensor controller for target tracking. In [19], artificial potential fields are introduced to compute virtual forces among sensors with a case study showing the feasibility of using virtual forces for target tracking.

In the area of bionanosensor networks, target tracking has not been fully investigated. Related work includes design and analysis of the collective behavior of mobile bionanosensors to achieve a high spatial occupancy to locate a target [20–22], a mobile nanonetwork based on mobile bionanosensors to transfer DNA messages [23,24], multihop communication and routing using mobile bionanosensors [25], and bionanosensor networks for detecting randomly moving signal molecules [26,27].

Our early efforts for the first time in the literature proposed the problem of target tracking. In [9,10], we first demonstrated through an individual-based modeling approach that a group of bionanosensors interacts through the use of two types of signaling molecules for target tracking: *attractants* to recruit bionanosensors to a location in the environment and *repellents* to spread bionanosensors from a location over the environment. While the individual-based modeling approach provides flexibility in modeling individual behaviors, it is computationally expensive and not scalable to the number of individuals (e.g., bionanosensors and targets). To reduce the computational cost, we then developed a partial differential equation (PDE)-based model [11] to describe autonomous mobile bionanosensor networks for target tracking.

In this paper, we extend our early efforts based on the PDE-based approach. We first describe a PDE-based model of target tracking for a two-dimensional area, then perform numerical experiments to understand the group behavior of bionanosensors, and finally apply the understanding to target tracking. Numerical results shown in this paper reveal how model parameters impact the target tracking performance and provide an insight into how bionanosensors may be designed and engineered for target tracking.

The remainder of this paper is organized as follows. Section 2 gives an overview of autonomous mobile bionanosensor networks for target tracking using an illustrative example. Section 3 then describes in detail a mathematical model of autonomous mobile bionanosensor networks for target tracking. Section 4 presents numeral results and analyzes the results to understand the collective behavior of mobile bionanosensors for target tracking. Section 5 gives a brief summary of this work and concludes this paper.

2. Overview

The bionanosensor network considered in this paper consists of a number of autonomous mobile bionanosensors distributed in a monitoring environment where targets are present. The goal of the bionanosensor network is to locate targets and continuously track the targets if they move.

In the monitoring environment, bionanosensors coordinate their behavior by using two types of signaling molecules: repellents and attractants. Bionanosensors release the repellents to spread over the monitoring environment (e.g., in search of targets), while they release attractants to gather in a specific location (e.g., around a target) in the environment. Both types of signaling molecules form concentration gradients in the monitoring environment that impact the mobility patterns of bionanosensors.

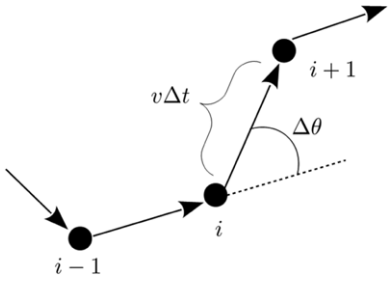

Fig. 1. Mobility model of bionanosensors. Locations of a bionanosensor at discrete times $i-1, i, i+1$ are shown.

One approach to modeling the bionanosensor network described above is to use individual-based models [9,10]. For example, bionanosensors may be modeled as an individual object with a direction of movement θ and the constant velocity v (Fig. 1). A sample simulation run from the individual-based model is shown in Fig. 2. The panels illustrate that (1) 100 bionanosensors and one target are placed at two separate locations; (2) the bionanosensors spread over the environment (e.g., using repellents) ($t = 100$ s), and one of the bionanosensors detects the target ($t = 1300$ s) and starts releasing attractants; (3) the nearby bionanosensors are attracted based on the concentration gradient of the attractants to the location of the target and the target is located ($t = 1600$ s); and (4) the group of bionanosensors moves to the target as the target moves ($t = 2400$ s). Fig. 3 shows how the number of bionanosensors in the proximity of the target (the number of bionanosensors found within the circle in Fig. 2) changes during the course of the simulation run.

Although the individual-based modeling approach provides flexibility in modeling individual behaviors, it does not scale to the number of individuals (e.g., the number of bionanosensors and targets) due to the highly expensive computational cost. In this paper, we develop an alternative, macroscopic model using a set of PDEs, which can scale to the number of bionanosensors and targets.

3. Model equations

We extend the one-dimensional model of bionanosensor networks for target tracking [11] to a two-dimensional model. The extended model shown in this section describes the rates of changes in concentrations of bionanosensors, attractants and repellents, respectively denoted as $C_b(=C_b(x, y, t))$, $C_a(=C_a(x, y, t))$ and $C_r(=C_r(x, y, t))$. See below and Table 1 for more details.

3.1. Dynamics of bionanosensor concentration

Bionanosensors diffuse based on the concentration gradients of attractants and repellents in the two-dimensional area. Bionanosensors are neither produced nor lost in the