Bacterium-based Mobile Bionanosensor Networks for Target Tracking: A Biologically Realistic Model

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ABSTRACT

This paper uses a biologically realistic model of chemotactic bacteria to design and evaluate a bacterium-based mobile bionanosensor network for tracking a moving target. The bacterium-based bionanosensor starts releasing chemoattractant, upon detecting a target, to create the concentration gradient of chemoattractant around the target. It also shows chemotactic responses to the concentration gradient to move toward the higher concentration of chemoattractant. Computer simulation results show that a group of bionanosensors collectively performs target tracking, demonstrating feasibility that such bionanosensors can be designed from chemotactic bacteria.

Keywords

Target tracking, molecular communication, nanonetwork, collective behavior, chemotaxis

1. INTRODUCTION

In bionanosensor networks, bio-nanomachines function as sensor and actuator devices to perform application functionality [1, 2]. Bio-nanomachines that form bionanosensor networks are nano- to microscale devices made of biomaterials and capable of interacting with chemical signals in the environment. Examples of bio-nanomachines include synthetic molecular complexes, artificial cells, and genetically engineered cells. Since bio-nanomachines are compatible with biological environments and operate based on chemical energy, applications in biomedical areas are highly anticipated.

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In this paper, we consider a mobile bionanosensor network for target tracking [5, 6]. The mobile bionanosensor network consists of mobile bio-nanomachines, simply referred to as mobile sensors in the rest of the paper. Mobile sensors are capable of actively moving in the environment (e.g., within a human body) as well as releasing and reacting to molecules in order to coordinate their behavior. A target is also a mobile biological object (e.g., a pathogen, infectious microorganism, or artificial biological device) and its presence is assumed to be a potential threat to the environment.

One challenge in mobile bionanosensor networks is to design a mechanism by which a group of mobile sensors collectively move to perform application functionality. Previous work shows that molecular communication [4] may apply to induce the coordinated movement [5, 6, 8, 9]. For instance, our previous studies [5, 6] introduce two types of signaling molecules, repellent and attractant, to coordinate the behavior of mobile sensors for target tracking (Fig. 1): (a) a group of mobile sensors is placed in the monitoring environment where a target exists, (b) the mobile sensors first spread over the environment using repellents, and as a result, one of the of sensors detects the target, (c) the mobile sensor, upon detecting the target, starts releasing attractants and nearby mobile sensors are attracted to the location of the mobile sensor, and (d) as the target moves, mobile sensors use repellents and attractants in the same manner to chase the target. Simulation experiments demonstrate that a group of mobile sensors is able to perform target tracking when model parameters are properly tuned.

Our previous studies however oversimplify the model of mobile sensors; a simple rotational diffusion model of chemotactic bacteria is extended to incorporate interactions through

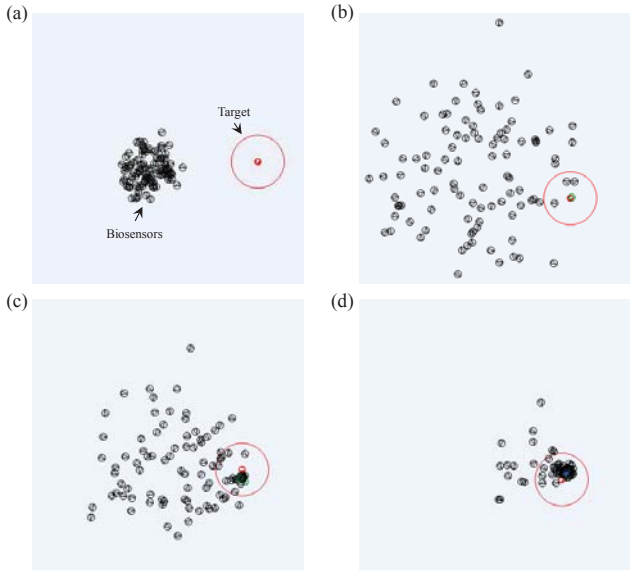

Figure 1: Target tracking processes [5]

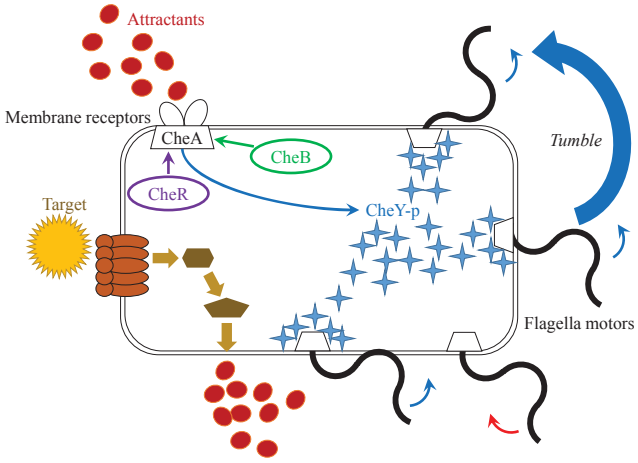

Figure 2: Bacterium-based mobile sensor

the attractant and repellent. In this paper, we use a biologically realistic model of *Escherichia coli* bacteria [7] to examine whether the bacteria can be used to design mobile sensors for target tracking.

The rest of the paper is organized as follows. Section 2 first describes a biologically realistic model of a bacterium-based mobile sensor designed for target tracking. Section 3 then uses the model to perform computer simulation and examines the feasibility of using bacteria for target tracking. Section 4 then briefly describes future work and concludes this paper.

2. MODELING BACTERIUM-BASED MOBILE SENSORS

Fig. 2 shows the model of a bacterium-based mobile sensor considered in this paper. A mobile sensor starts releasing attractant upon detecting a target, and it continues to release attractant for a pre-defined duration, T. For simplicity, we assume a mobile sensor produces a steady state concentration gradient by releasing attractant at a constant rate in a three-dimensional space. The concentration of attractant released by a mobile sensor in this case decreases in proportion to the inverse of distance r from the mobile sensor [3]:

$$C(r) = \frac{N}{4\pi D r} = \frac{\alpha}{r}, \quad (1)$$

where N is the rate at which the mobile sensor releases attractant, D is the diffusion coefficient of the attractant, and $\alpha = \frac{N}{4\pi D}$ is introduced to simplify the expression.

A mobile sensor shows chemotactic responses according to the chemotactic model of *Escherichia coli* bacteria described in [7]. It uses an ordinary differential equation to describe the intracellular signaling dynamics involving chemotaxis proteins such as CheA, CheB, CheR and CheY. Briefly, the concentration of attractant in the environment affects the activity level of the receptor cluster containing CheA in the bacterium. The concentrations of CheB and CheR inside the bacterium also affect the activity level of the receptor cluster through methylation and demethylation, respectively. The active CheA phosphorylates the CheY by transferring its phosphate group to CheY, and thus the concentration of active CheA impacts that of CheY-p (the phosphorylated CheY). The model also describes the stochastic motor switching based on the concentration of CheY-p. The bacterium has a set of flagella motors, and based on the concentration of CheY-p each flagella motor changes the rotating direction between the clockwise and counter clockwise. A voting model is adopted to determine the mode of movement; namely, the bacterium *runs* to maintain its current moving direction if majority of flagella motors rotate clockwise and *tumbles* to randomize the direction, otherwise.

3. SIMULATION RESULTS

In each target tracking experiment, we place a group of 100 mobile sensors all at the center in a 20 (mm) $\times$ 20 (mm) two-dimensional space. We also place a single moving target in the two-dimensional space, performing a linear motion along an axis at the velocity of v.

For parameter values, we use $T = 50$ (sec) for the time duration that a mobile sensor releases attractant after it detects a target and $\alpha = 1$ for the parameter in (1). These two parameter values are arbitrary chosen and they remain to be determined after the type of attractant and the mechanism to release attractant are identified. For other model parameters, we use the default values used in simulation experiments described in [7].

In each simulation run, we observe how the averaged sensor-to-target distance changes over time. Fig. 3 shows simulation results obtained with the moving velocity of the target $v \in \{0.005, 0.01, 0.02, 0.05\}$ (mm/sec). Here each mobile sensor moves at the velocity of 0.02 mm/sec. The figure shows that for $v = 0.005$ the group of mobile sensors is able to keep the averaged distance to the target within 0.5 mm, indicating that target tracking is feasible for at least 3000 sec. As v increases to 0.01, however, the averaged sensor-to-target distance tends to increase over time. When $v = 0.02$

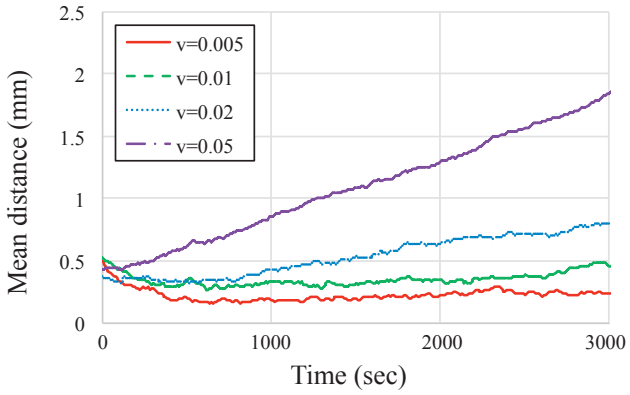

Figure 3: Averaged sensor-to-target distance vs. time. v (mm/sec) is the moving velocity of the target.

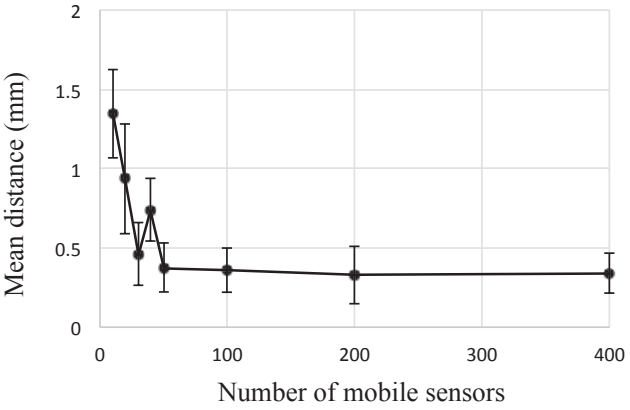

Figure 4: Impact of the number of mobile sensors on the averaged sensor-to-target distance

and 0.05 (mm/sec), the averaged sensor-to-target distance clearly increases, showing that target tracking is not feasible.

The number of mobile sensors deployed in the environment impacts how long they can track a moving target. Fig. 4 shows simulation results where the averaged sensor-to-target distance at 3000 sec is plotted for a given number of mobile sensors. Here the target moves at 0.01 mm/sec and each mobile sensor at 0.02 mm/sec. The simulation results show that target tracking is possible with about 50 mobile sensors and that a larger number of mobile sensors (e.g., 200 or 400) may not be necessary.

4. CONCLUSION

In this paper, we use a biologically realistic model of chemotactic bacteria to demonstrate feasibility that mobile sensors for target tracking can be designed and engineered from chemotactic bacteria. Our future work will further address other practical aspects that are not considered in this paper. For example, the individual behavior of bacterium-based mobile sensors (e.g., their sensitivity to attractants) may differ due to phenotypic differences, which may affect their collective behavior. Also, bacterium-based mobile sensors may grow, divide and die during the target tracking operation. These aspects need to be examined or considered in future work. Finally, it is important to engineer mobile sensors from bacteria and experimentally demonstrate the target tracking processes to show the feasibility.

5. ACKNOWLEDGMENTS

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