

Performance Analysis of Remote Monitoring and Mobile Object Tracking in Wireless Sensor Network

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Abstract--Target Tracking is an important problem in sensor networks, where it dictates how accurate a targets position can be measured. In response to the recent surge of interest in mobile sensor applications, this paper studies the target tracking problem in a mobile sensor network (shortly called as MSN), where it is believed that mobility can be exploited to improve the tracking resolution. This problem becomes particularly challenging given the mobility of both sensors and targets, in which the trajectories of sensors and targets need to be captured. We derive the inherent relationship between the tracking resolution and a set of crucial system parameters including sensor density, sensing range, sensor and target mobility. We investigate the correlations and sensitivity from a set of system parameters and we derive the minimum number of mobile sensors that are required to maintain the resolution for target tracking in an MSN. The simulation results demonstrate that the tracking performance can be improved by an order of magnitude with the same number of sensors when compared with that of the static sensor environment.

Keywords:- Mobile sensor network, Network and mobility Model, Target Tracking Device, Sensitivity Analysis

I. INTRODUCTION

The development of sensor network technology has enabled the possibility of target detection and tracking in a large-scale environment. There has been an increased interest in the deployment of mobile sensors for target tracking, partly motivated by the demand of habitat monitoring and illegal hunting tracking for rare wild animals. In this paper, we are primarily interested in target tracking by considering both moving targets and mobile sensors. Specifically, we are interested in the spatial resolution for localizing a target's trajectory. The spatial resolution refers to how accurate a target's position can be measured by sensors, and defined as the worst-case deviation between the estimated and the actual paths in wireless sensor networks.

Our main objectives are to establish the theoretical framework for target tracking in mobile sensor networks, and quantitatively demonstrate how the mobility can be exploited to improve the tracking performance. Given an initial sensor deployment over a region and a sensor mobility pattern, targets are assumed to cross from one boundary of the region to another. We define the spatial resolution as the deviation between the estimated and the actual target traveling path, which can also be explained as the distance that a target is not covered by any mobile sensors.

Given the mobility of both targets and sensors mobility, it is particularly challenging to model such a stochastic problem for multiple moving objects. Furthermore, we are also interested in determining the

minimum number of mobile sensors that needs to be deployed in order to provide the spatial resolution in mobile sensor networks. It turns out that our problem is very similar to the collision problem in classical kinetic theory of gas molecules in physics, which allows us to establish and derive the inherently dynamic relationship between moving targets and mobile sensors. The binary sensing model of tracking for wireless sensor networks has been studied in several prior works. The work in showed that a network of binary sensors has geometric properties that can be used to develop a solution for tracking with binary sensors. Another work also considered a binary sensing model. It employed piecewise linear path approximations computed using variants of a weighted centroid algorithm, and obtained good tracking performance if the trajectory is smooth enough.

A follow-up work explored fundamental performance limits of tracking a target in a two-dimensional field of binary proximity sensors, and designed algorithms that attained those limits. Prior works in stationary wireless sensor networks have studied the fundamental limits of tracking performance in term of spatial resolution.

Our focus in this paper is completely different from all prior works. There are two distinctive features of our work: 1) we try to identify and characterize the dynamic aspects of the target tracking that depend on both sensor and target mobility; 2) we consider tracking performance metrics: spatial resolution in a mobile sensor network. By leveraging the kinetic theory from physics, we model the dynamic problem and examine its sensitivity under different network parameters and configurations. To the best of our knowledge, we believe this is a completely new study of target tracking in mobile sensor networks.

The rest of this paper is organized as follows. Section II describes the network and mobility model, as well as defining the target tracking problem in a mobile sensor network. Section III formulates the target tracking problem. Section IV examines the tracking performance sensitivity under different network parameters and configurations, and finally Section V concludes the paper.

II. NETWORK AND MOBILITY MODEL

Target Tracking is an important problem in sensor networks, where it dictates how accurate a targets position can be measured. In response to the recent surge of interest in mobile sensor applications, this paper studies the target tracking problem in a mobile sensor network (MSN), where it is believed that mobility can be exploited to improve the tracking resolution. This problem becomes particularly challenging given the mobility of both sensors and targets, in which the trajectories of sensors and targets need to be captured. We derive the inherent relationship between the

tracking resolution and a set of crucial system parameters including sensor density, sensing range, sensor and target mobility.

We consider a mobile sensor network (MSN) to consist of N (A) mobile sensors initially placed inside a two dimensional geographical region A shown in Figure 1.

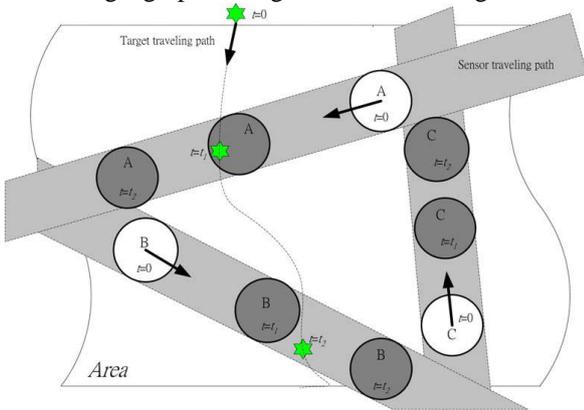


Fig. 1: Example of target tracking problem in a mobile sensor network.

The region can be in any convex shapes under the proposed formulation. To keep it mathematically tractable, we assume A is a rectangular region, which has four boundaries. We assume the width of the area to be W and the length to be $|A|/W$, where $|A|$ represents the area of the region. For the initial configuration (at time $t = 0$), we assume sensors are independently deployed at a random uniform distribution. Under this assumption, the sensor location can be modeled by a stationary two-dimensional Poisson process. Denote the density of the Poisson process as n_A . The number of sensors located in the region A , $N(A)$, follows a Poisson distribution of parameter $n_A \cdot |A|$. $\Pr(N(A) = k) = \frac{e^{-n_A |A|} (n_A |A|)^k}{k!}$, where k is a non-negative integer.

We define $\Pr(Y)$ to be the probability that event Y occurs, and $\Pr(\bar{Y}) = 1 - \Pr(Y)$. The two dimensional Poisson process results random uniform distribution sensor deployment at time $t = 0$. Our emphasis is on discovering the tracking performance in an MSN, and therefore we abstract away lower layer networking issues, such as the communication overhead and the network architecture of the sensors.

A. Sensing And Mobility Model:

We assume that each sensor has a *sensing region* and can only sense the environment and detect events within that region. A target is any object that is subject to sensor detection and tracking as it travels in the region. It is said to be *covered* or *detected* by a sensor if it has been located inside the sensing region of the sensor. We assume the sensing region to be a disk of radius R centered at the sensor. This definition is usually referred to as a binary or disc-based sensing model. In the target tracking formulation in this paper, we essentially define probabilistic tracking. Ideally, a probabilistic sensing model such as the one in would be more appropriate. For simplification and mathematical tractability, we adopt the disc based sensing model in this work. In an MSN, depending on the mobile platform and application scenario, sensors can choose from a wide variety of mobility strategies, from passive movements to highly coordinated and complicated motion.

Sensors deployed in the air, ocean or on wild animals move passively according to external forces such as air, ocean currents or wild animal movement patterns.

The movement patterns are referred as the uncontrolled sensor mobility model; simple robots may have a limited set of mobility patterns, whereas advanced robots can navigate in a more complicated itinerary. The movement patterns are referred as the controlled sensor mobility model. In this work, we consider the following uncontrolled sensor mobility model. We assume that sensors move independently of each other, without any coordination between them. The movement of a sensor is characterized by its speed and direction. A sensor randomly chooses a direction $\theta \in [0, 2\pi)$ according to the distribution with probability density function $P\Theta(\theta)$. The speed of the sensor is randomly chosen from a range $v_m \in [0, v_{max} m]$, according to a probability density function of $PV_m(v_m)$ and $v_{max} m$ is the maximum sensor speed. A sensor travels to the boundary of area A at a chosen speed and direction. Once the boundary is reached, the sensor bounds back, by choosing another angular direction and continue the process. We refer to the above model as the random direction mobility model. Target movement is assumed to follow a crossing path, which is defined as a path (line segment) crossing from one boundary to another. We assume the velocity of a target is a constant v_t . As it will become clear in Section III, from our formulation of this paper, the target movement is not explicitly restricted to any specific mobility model; instead the most relevant parameter is the length of the path. For the mathematical tractability, it is assumed that the target mobility is independent of the sensor mobility. In reality, however, there could be spatial and temporal correlations on the mobility pattern, which are not captured in this formulation.

The movement patterns are referred as the uncontrolled sensor mobility model; simple robots may have a limited set of mobility patterns, whereas advanced robots can navigate in a more complicated itinerary. The movement patterns are referred as the *controlled* sensor mobility model. In this work, we consider the following uncontrolled sensor mobility model. We assume that sensors move independently of each other, without any coordination between them. The movement of a sensor is characterized by its speed and direction.

B. Tracking Measurement:

We define the spatial resolution in MSNs as the average deviation between the estimated and the actual target travel paths, which is an extension of wireless sensor networks (WSNs). Under our network model, the deviation between the estimated and the actual paths can be illustrated as the distance that a target is not covered by any sensors. The target is covered by sensors under the time periods (t_1 to t_2) and (t_3 to t_4), while it cannot be localized by any sensors before t_1 , after t_4 and between t_2 to t_3 . The average deviation can then be obtained by the average travel distance during those time periods. We then define uncovered distances as the travel distances of a target between successive sensor coverage. In this work, we use the average deviation instead of the maximum deviation for the study of spatial resolution in MSNs. As it becomes clear in Section III, from the proof, the probability distribution function of the deviation is an exponential function. The maximum

deviation tends to infinite with certain probability, which makes the definition of spatial resolution meaningless if we directly extend the definition from WSNs.

III. TARGET TRACKING IN A MOBILE SENSOR NETWORK

In this section, we formulate the target tracking problem in an MSN. The problem is similar to a problem in classical kinetic theory of gas molecules in physics, specifically, the mean free path theory. For comparison, we can treat a mobile sensor as a gas molecule, and a target as an electron.

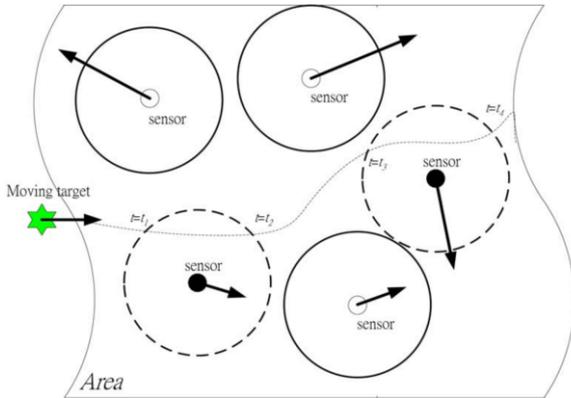


Fig. 2: The spatial resolution of a mobile sensor network.

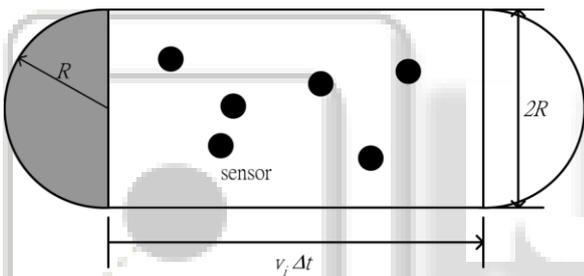


Fig. 3: An effective coverage region with sensing range R at time $t = \tau$.

A. Spatial Resolution:

Our objective is to formulate the spatial resolution in MSNs. This can be achieved by modeling the average deviation between the estimated and the actual target travel paths, which is the average travel distance of a target between successive coverage by mobile sensors. We use the notation λ to represent the average travel distance of a target between successive sensor coverage. We first assume sensors are stationary and relax the assumption in the latter part of this section, then extend our formulation to consider sensor mobility. Recall that the sensing range is R , when $t = 0$, a cross section of coverage can be modeled by using a circle with the diameter $2R$. The concept of cross section is used to express the likelihood of coverage between a target and the sensors. After a period of time Δt , the circle swept out an area (shown in Figure 3) and the amount of sensor coverage can be estimated from the density of mobile sensors ($n_A = N(A)/A$) inside the area.

B. Relative Speed Under The Random Direction Mobility Model:

So far we have discussed the generalized formulation without a specific sensor mobility model; we now proceed to calculate the average relative speed under the random direction mobility model. However as illustrated previously, this can be applied to other mobility models. The speed of a

moving target relative to mobile sensors varies only with the angle between their respective directions of movement, which is shown in Figure 4a. Since the mobile sensors move randomly in all possible directions (due to the random directional mobility model), a fraction $d\theta/2\pi$ of them move in directions that are within angle θ of the target v_i direction.

IV. SENSITIVITY ANALYSIS AND SIMULATION RESULTS

The formulation in the previous section mainly presents the dynamic aspects of the target tracking problem in an MSN. In this section, we investigate the correlations and sensitivity of the spatial resolution from a number of critical system parameters. Specifically, in this section we study the relationships between spatial resolution, the density of sensors and sensor mobility. We first study the correlation between the density of mobile sensors and the tracking performance. The spatial resolution is inversely proportional to the density of sensors (n_A) and the sensing range (R). The formulation is consistent with the WSN results when we consider zero mobility of sensors. From this prior work, the order of the spatial resolution bound in WSNs is also $1/n_A \cdot R$. We next analyze the correlation between sensor speed and tracking performance. The spatial resolution is inversely proportional to the average relative velocity (v_{rel}), at the same time, the average relative velocity is affected by both the speed of the sensors and the targets (v_m and v_i). The relationships between the average uncovered distance, the sensor speed and the target speed. The average uncovered distance decreases slowly starting at $v_m \rightarrow 0$, and the negative slope of the line increases when the sensor speed is faster than the target speed.

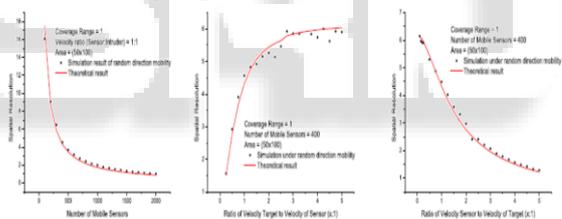


Fig. 4:

V. CONCLUSIONS

In this paper, we have studied the target tracking problem in mobile sensor networks. Specifically, we introduce performance metrics: spatial resolution and we investigate the resolution against moving targets. By modeling the dynamic aspects of the target tracking that depend on both sensor and target mobility, we derive the inherent relationship between the spatial resolution and a set of crucial system parameters including sensor density, sensing range, sensor and target mobility.

VI. FUTURE WORK

The results demonstrated that mobility can be exploited to obtain better spatial resolution. There are several avenues for further research on this problem: (1) to consider the detection error of mobile sensors under varying sensor speeds. This can be formulated into an optimization problem for target tracking; (2) to refine the sensor mobility model, the network model, and the communication model among sensors in order to enable effective detection and tracking. For example, a practical distributed target tracking and

sensing information exchange protocol becomes an interesting future research topic when sensors are required to trace the target paths.

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