Target Tracking Problem in a Mobile Sensor Network (MSN)

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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.

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.

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.

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 ($t1$ to $t2$) and ($t3$ to $t4$), while it cannot be localized by any sensors before $t1$, after $t4$ and between $t2$ to $t3$. 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.

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 circle swept out an area and the amount of sensor coverage can be estimated from the density of mobile sensors inside the area.

In order to calculate the average uncovered distance in an MSN, it is necessary to assess the average *relative velocity* of mobile sensors with respect to moving targets. The relative velocity can be expressed in terms of the targets' and sensors' velocity vectors. Different sensor mobility models can result in different relative velocity formulations. In this paper, for simplification, we use the random direction mobility model to describe mobile sensor movement. We consider the case with homogeneous velocity of mobile sensors and calculate the coverage rate.

The general formulation, however, is not restricted to a specific mobility model and velocity assumption, as sensor mobility with different speed distributions can also be captured under the gas kinetic framework, for example, the Maxwell-Boltzmann speed distribution. By recalculating the average relative speed under the distribution and different mobility models, we can still use the theoretical framework to compute newly uncovered distance and the new coverage rate. Recall that the velocity vector of a target is denoted by *VI* and the speed of a mobility sensor. The sensor coverage per unit time is given and we need to replace the velocity v by the average relative speed of mobile sensors with respect to moving targets, which is denoted by the sensor coverage per unit time where S is the cross section of coverage between the target and mobile sensors.

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. Since the mobile sensors move randomly in all possible directions (due to the random directional mobility model), a fraction of them move in directions that are within angle *of* the target direction. Hence, for the average relative speed

C. Distribution of spatial resolution

To explain why we use the average deviation instead of the maximum deviation for the definition of spatial resolution in

MSNs, we study the probability distribution function of the uncovered distance. We consider a group of targets to be initially outside the region. Let the number originally in the group at time and at time *t*, *N* of them going without coverage by any mobile sensors. Then during the next time interval the *targets* are covered and drop out of the group, where *v* denotes the coverage rate for a target with speed. The change of *N* is which can be written as:

IV. Distributed Target Classification And Tracking In Sensor Networks

A. Face Discovery

First, each node collects the neighbor information by hello message. Next, each node computes its face neighbor nodes by Gabriel Graph (GG). The face neighbor node means the link between this node and its neighbor conforms to GG. Next, each node informs the computed face neighbor nodes to its neighbors. Each node decides its face neighbor nodes after these processes. Next, each node utilizes the right-hand neighborhood discovery protocol that is proposed in to construct adjacent faces. The face maintenance also follows after the face discovery; each node obtains the location information of spatial neighbors. This face discovery phase is performed in initial.

B. Target Discovery

This subsection discusses target discovery process. A source S wants to track a target o but it does not know the location of target o. Source S employs the sensor network to discover the target o. Source S issues a flooding request packet to seek target. The sensor network is synchronization and the sensors periodically synchronize to wake and to sleep. Source S issues a request packet in awaking period. The format of request packet is request (packet type, source id, sequence number, target information), where the packet type is Request, the sequence number is used to avoid forwarding the duplicate packet, the target information is used to identify target.

C. Target Detection

If a sensor n is a near-node and target o is in face Fa, this sensor n becomes an ingress node of Fa and tracks the target. If the sensors do not cooperate to detect the target, it maybe loses the target tracks while the target moves. For tracking the target accurately, sensor n asks its spatial neighbors for cooperating tracking target. Sensor n issues wakeup packet to wake it's all spatial neighbors of adjacent faces and asks them for detecting target o cooperatively.

D. Tracking Target

While a target o is tracked by source S, the sensor network has to record the target tracks. A source S obtains the target location that is informed from the first beacon node n (i.e. ingress node) after completing a target discovery process, and then S starts to move toward the first beacon node n's location. When S reaches the position of the first beacon node n, S queries the beacon node for next position.

E. Face-Track Shortening

This subsection discusses how to adjust face-track. When the velocity of target is faster than that of source, the source is very difficult to catch target. In the course of chasing, the face-track may be not the optimal tracks. Therefore, this work proposes a shortening method for face-track to make source chase target fast. The length of face-track will be shortened in this process.

F. Loop Face-Track removing

This subsection discusses the loop face-track problem. Wireless sensor networks (WSNs) have shown many attractive features in a lot of real-world applications that motivate their rapid and wide diffusion. One of the most challenging topics when dealing with WSNs is the localization and tracking of objects from measurements collected by the nodes themselves. Once distributed in a region without the knowledge of their positions, the nodes actively take part in the localization of the network as well as to the detection and monitoring of the presence and movements of targets lying within the sensed area. This paper reviews state-of-the-art systems and approaches developed for WSN-based localization and tracking of active as well as passive targets. The main focus is on systems that exploit the strength of the received signal, always available at the WSN nodes, without ad hoc or additional hardware. Recent strategies for WSN-based imaging are discussed as well.

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 and the sensing range. 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.

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.

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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