The Improvement of Target Tracking Resolution in Mobile Sensor Networks

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Abstract: Target Tracking is an important problem in sensor networks, where it dictates how accurate a target's 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 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 (MSN), Target Tracking.

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 [2]. 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 [3]. 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 [4] 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 [5] 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 in [6]. 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 target tracking problem in a mobile sensor network. Section III Challenges in Target Tracking Section IV examines the tracking performance sensitivity under different network parameters and configurations, and finally Section V concludes the paper.

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II. TARGET TRACKING

Target tracking is one of the most important applications of wireless sensor networks, such as healthcare, building and military monitoring, home security. So a lot of useful application can benefit greatly from accurate tracking. Considering the problem of single target tracking in controlled mobility sensor networks, researchers in have proposed a novel strategy which is based on the interval based estimation for managing sensors mobility to improve the estimation of the position of the target. Mobile sensors are able to move to a new position at each step, which is chosen within the computed set using ant colony optimization algorithm. The movement decision is made upon whether the new position will improve the estimation while minimizing the energy consumption or not. The proposed approach uses a hybrid sensor network. While mobile sensors are not only used for optimizing the performance of the target tracking but also maximizing the lifetime of the network, static sensors guarantee the whole coverage of the network. Usually, a target can be divided into two classes, i.e., cooperative target and non-cooperative target. The former one can broadcast cooperative signals (e.g., radio frequencies, vibrations, and sound, etc.) from time to time, which keeps on communication with the sensors for detecting the target. The latter one, in a lot of applications, many intelligent targets would not emit such kind of signals. In this case, the sensors have to actively detect the target by frequently broadcasting certain signals, such as infrared or ultrasonic waves. When the target is within the sensing range of the sensors, it can be detected. In this paper, we mainly focus on tracking a non cooperative target.

The target tracking problem under insufficient anchor coverage is first summarized in, which aims to propose a target tracking framework for insufficient anchor coverage and asynchronous networks so that improve the tracking accuracy. Due to lack of costly anchors and environment constraints, the target cannot be detected by more than three anchors simultaneously. So the authors design two kinds of strategies, i.e., one depends on sufficient anchors, while the other can be implemented on insufficient anchors which can be formulated as an optimal path searching problem in a graph present optimal centralized motion strategies for solving the problem of multiple mobile sensors cooperatively for tracking a moving target using distance-only measurements. The authors employ the trace of the targets position estimate covariance matrix as the object function. The performance is measured by the scope of the uncertainty for the targets position. In addition, the authors also account for the velocity constraints on mobile sensors. Different from precious work, the impose constraints on the minimum distance at which the mobile sensors are allowed to be close to the target. Besides, the authors adopt measurements extend to a mixture of relative observations, including distance-only, bearing-only, and distance-and-bearing measurements.

Our previous work propose an integrated control approach which allows the mobile sensors adjust their positions according to sensing quality, communication quality and area coverage. In combine these three performance metrics together as the cost function. The decentralized motion algorithm in this case is based on the gradient descent of the cost function with the constant step-size of 1. However, the authors do not consider the speed constrains on the motion of the mobile sensors. And the work extends the idea. The authors design the coordinative moving strategy which minimizes the sensing quality while guaranteeing specified coverage quality in centralized way. In addition, considering the velocity constrains on the target and the mobile sensors, the authors employ multi-step optimization and moving multiple sensors to improve the tracking performance. In this paper, our objective is to design the coordinative moving strategy which guarantees the target can be detected in each observed step while minimizing the amount of moving sensors. Since accurately predicting the motion of the target over multiple steps is impossible, we pay much attention on the problem by which the mobile sensors are assigned the optimal destinations at each step.

Specifically, in order to reduce the energy consumption throughout the network, we aim to minimize total traveled distance at each step. The major contributions of this paper can be summarized as follows:

1. Different from previous work, we take sensing quality, the number of moving sensors and the total traveled distance at each time step into consideration. We formulate the problem into one which aims to ensure the target will not be lost while minimizing the amount of sensors to move and then the total traveling distance of all moving sensors each step.
2. We make full use of the mobility of mobile sensors in solving the optimization tracking problem. In this framework, the tracking problem can be transformed into deployment problem and then the tracking task is formulated as assigning minimum number of mobile sensor to achieve both certain coverage requirement and the total traveled distance requirement.
3. The performance of the proposed method is evaluated by 3D display simulator. And a simulation system which is implemented for verification is close to the realistic scenarios.

III. CHALLENGES IN TARGET TRACKING

The challenge of target tracking and mobile sensor navigation arises when a mobile target does not follow a predictable path. Successful solutions require a real-time location estimation algorithm and an effective navigation control method. Target tracking can be viewed as a sequential location estimation problem. Typically, the target is a signal emitter whose transmissions are received by a number of distributed sensors for location estimation. A large scale tracking system with sensors gives rise to a number of design challenges with constraints specific to
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In this section, we discuss scenarios with sensor networks. In this section, we discuss them in detail and lay the groundwork for our proposed protocol for target tracking. We describe the various issues associated with sensor networks that need to be addressed by any protocol being developed for application in sensor networks. We comment on general requirements of such protocols and also on issues specific to the scenario of target detection using sensor networks. Advances in the fabrication and integration of sensing and communication technologies have facilitated the deployment of large scale sensor networks. With their capability for pervasive surveillance, control of physical systems and economical large scale deployment, sensor networks and their applications have tremendous potential in both commercial and military environments.

However, the need to coordinate such large networks as well as their inherent limitations like power constraints, distributed coordination and ad hoc deploy ability lead to a number of challenges in the design and deployment of sensor networks. In addition, the application specific communication and system requirements may put additional constraints on the design and coordination of such networks. In this paper, we address the issue of scalable coordination and operation of a large scale sensor network specifically designed to track mobile targets. One of the most important areas where the advantages of sensor networks can be exploited is for tracking mobile targets. Scenarios where such network may be deployed can be both military (tracking enemy vehicles, detecting illegal border crossings) and civilian (tracking the movement of wild animals in wildlife preserves). Typically, for accuracy, two or more sensors are simultaneously required for tracking a single target, leading to coordination issues. Additionally, given the requirements to minimize the power consumption due to communication or other factors, we would like to select the bare essential number of sensors dedicated for the task while all other sensors should preferably be in the hibernation or off state.

In order to simultaneously satisfy the requirements like power saving and improving overall efficiency, we need large scale coordination and other management operations. These tasks become even more challenging when one considers the random mobility of the targets and the resulting need to coordinate the assignment of the sensors best suited for tracking the target as a function of time. In this paper we propose architecture for managing and coordinating a sensor network for tracking moving targets. However, the proposed architecture is quite general and can be easily adapted for use in other applications. The power limitation due to the small size of the sensors, the large numbers of sensors which need to be deployed and coordinated, and the ability to deploy sensors in an ad-hoc manner give rise to a number of challenges in sensor networks. Each of these needs to be addressed by any proposed architecture in order for it to be realistic and practical.

1. Scalable Coordination
A typical deployment scenario for a sensor network comprises of a large number of nodes reaching in the thousands to tens of thousands. At such large scales, it is not possible to attend to each node individually due to a number of factors. Sensors nodes may not be physically accessible, nodes may fail and new nodes may join the network. In such dynamic and unpredictable scenarios, scalable coordination and management functions are necessary which can ensure a robust operation of the network. In the light of target tracking, the coordination function should scale with the size of the network, the number of targets to be tracked, number of active queries etc.

2. Tracking Accuracy
To be effective, the tracking system should be accurate and the likelihood of missing a target should be low. Additionally, the dynamic range of the system should be high while keeping the response latency, sensitivity to external noise and false alarms low. The overall architecture should also be robust against node failures.

3. Ad Hoc Deploy ability
A powerful paradigm associated with sensor networks is their ability to be deployed in an ad hoc manner. Sensors may be thrown in an area affected by a natural or manmade disaster or air dropped to cover a geographical region. Thus sensor nodes should be capable of organizing themselves into a network and achieving the desired objective in the absence of any human intervention or fixed patterns in the deployment.

4. Computation and Communication Costs
Any protocol being developed for sensor networks should keep in mind the costs associated with computations and communication. With current technology, the cost of computation locally is lower than that of communication in a power constrained scenario. As a consequence, emphasis should be put on minimizing the communication requirements.

5. Power Constraints
The available power in each sensor is limited by the battery lifetime due to the difficulty or impossibility of recharging the nodes. As a consequence, protocols which tend to minimize the energy consumption or power aware protocols which adapt to the existing power levels are highly desirable. Additionally, efforts should be made to turn off the nodes themselves if possible in the absence of sensing or coordination operations.

In the next section, we present our proposed architecture for scalable and accurate tracking of mobile targets. The protocol specifically aims at minimizing the communication and control overheads while using a cluster based approach to achieve scalability.
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. From the spatial resolution is inversely proportional to the density of sensors ($n_s$) and the sensing range ($R$). The formulation is consistent with the WSN results from [3], when we consider zero mobility of sensors. From this prior work, the order of the spatial resolution bound in WSNs is also $\frac{1}{n_sAR}$ (fig 1 and 2).

Fig.1. Incomplete elliptic integral function and average relative speed ($\overline{V_{rel}}$) against ratio of sensor speed to target speed.

Fig.2. Fraction of the original $N_0$ targets that are still going after traveling distance $l$ without detected by sensors.

Fig.3. The 3D plot for spatial resolution, target speed and sensor speed.

Fig.4. The spatial resolution against density of sensor.

Fig.5. The spatial resolution against ratio of target speed to sensor speed.
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![Graph showing the relationship between spatial resolution and sensor speed](image)

**Fig.6. The spatial resolution against ratio of sensor speed to target speed.**

We next analyze the correlation between sensor speed and tracking performance. From the spatial resolution is inversely proportional to the average relative velocity ($\overline{v}_{rel}$), at the same time, the average relative velocity is affected by both the speed of the sensors and the targets ($v_m$ and $v_t$). Fig.3 plots 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. We present numerical results verified by simulations. We develop a simulator that captures the essence aspects of the MSNs described. The simulator also provides the flexibility in selectively changing the configuration with different parameter settings including: (i) the area size and dimension of $A$; (ii) the number of mobile sensors ($N(A)$); (iii) the coverage range of a sensor ($R$); (iv) the mobility of targets; (v) and the mobility of sensors. Unless otherwise specified, we use the following default settings: we deploy 200 mobile sensors randomly distributed in an area of size 50x100 with the coverage range of sensors $R = 1$. Figs 4, 5 and 6 illustrate the spatial resolutions against density of sensor, ratio of target speed to sensor speed, and ratio of sensor speed to target speed, respectively. The calculated spatial resolutions are also almost the same as the simulation results. The results also show that sensor mobility can be exploited to compensate for the lack of sensors and improve tracking performance.

**V. CONCLUSION**

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.

**VI. REFERENCES**