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Constructing perimeter barrier coverage with bistatic radar sensors ☆

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ABSTRACT

Perimeter barrier coverage is widely used in many surveillance and intruder detection applications. In this paper, we study how to achieve perimeter barrier coverage with bistatic radar sensors. Much different from the binary disk and sector coverage, the coverage area of bistatic radar is dependent on the distance between a pair of radar transmitter and receiver. We first study the minimum cost bistatic transmitter–receiver placement problem. We prove the optimal placement pattern and the structure property of a minimum cost placement sequence. When manually placing radars is not applicable, we study the mobile radar movement problem for perimeter barrier coverage with the objective of minimizing the total moving distance or maximal moving distance. To solve the movement problems, we propose two algorithms to first determine the target locations and then use bipartite graph approach to find the best movement schemes. We also provide performance bounds of our movement solutions to the optimal solutions. Our solutions to the placement and movement problems are also validated via simulation results.

1. Introduction

Barrier coverage is an important issue for intrusion detection applications in wireless sensor networks (Wang, 2011; Zhu et al., 2012). In order to detect any intruder traversing a protected field, a chain of sensors should be deployed such that their covered area can form a continuous barrier (Kumar et al., 2007). Depending on different application scenarios, stationary sensor nodes can be manually placed at desired locations, or mobile sensor nodes can automatically move to desired locations to construct barrier coverage for a region of interest.

Some previous studies on barrier coverage have assumed a *disk coverage model* (Liu et al., 2008; Saipulla et al., 2013; He and Shi, 2012) or *sector coverage model* (Tao et al., 2012; Wang and Cao, 2011; Chang et al., 2012) for each single sensor. In the disk model, a sensor can cover a disk centered at itself with the radius of the sensing range; while in the sector model, a sensor can cover a sector of such a disk. The barrier coverage can be achieved, if we can find at least a continuous curve from a chain of sensors' overlapped coverage disks or sectors such that the curve can cross or surround a region of interest. How to efficiently construct a disk or sector barrier has been the main research focus in the past years (He and Shi, 2012; Cheng and Tsai, 2012).

Recently, radar sensor networks are becoming a new research focus (Skolnik, 2002). A radar sensor can emit radio waves and collect echoes. When an intruder appears, the echo will be different from the one without the existence of an intruder. By examining the collected echoes, a radar sensor can detect an intruder. There are two types of radar sensors: a monostatic radar contains both the radio transmitter and receiver; while the transmitter and receiver are separated at different locations for a bistatic radar (Willis, 2005). Due to the flexibility of separate deployment of the transmitter and receiver, bistatic radars are more often used in radar sensor networks (Baker and Griffiths, 2006; Liang and Liang, 2011).

The coverage model of a bistatic radar is much different from the disk or the sector model. The covered area of a bistatic radar is dependent on the locations of both transmitter and receiver, which can be characterized by a Cassini oval, as shown in Fig. 1(a). Furthermore, a receiver can potentially couple with different transmitters. Previous studies on coverage based on bistatic radars focus on the optimal placement of given number of transmitters and receivers for minimizing the maximum distance product between some *points of interest* and their closest transmitter–receiver pair (Tang et al., 2013), or minimizing the vulnerability of a straight line segment (Gong et al., 2013b).

In this paper, we study the problem of constructing perimeter barrier coverage with bistatic radars to provide protection of some region boundary. Perimeter barrier coverage is very efficient for many practical applications, such as coastal shorelines monitoring and international boundary surveillance (Wang et al., 2009, 2011), and is very efficient compared to area coverage which generally

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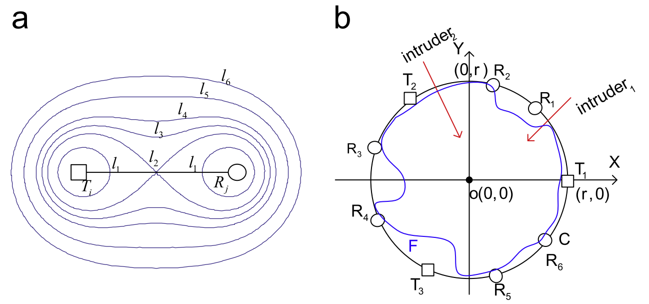

Fig. 1. (a) Illustration of the vulnerability contours of the (T_i, R_j) pair, where $l_1 < l_2 < l_3 < l_4 < l_5 < l_6$. (b) Perimeter barrier coverage node deployment.

needs to cover a whole region (Pham et al., 2011; Al-Turjman et al., 2013; Alam et al., 2014). In this paper, we study perimeter barrier coverage construction in some regions of interest whose irregular boundary can be represented by its minimum circumcircle, and bistatic radars are to be deployed on the circumcircle perimeter to construct a perimeter barrier coverage such that every point on the perimeter can be covered.

We first study the minimum cost radar placement problem, where bistatic radar transmitters and receivers can be manually placed on the circumcircle perimeter. The unit cost of a transmitter is generally larger than that of a receiver. Our objective is to determine the optimal number of bistatic transmitters and receivers and their locations in order to minimize the total placement cost, while guaranteeing the detection requirement. When manual placement is not applicable, we consider using mobile radar nodes for barrier construction. We then study two transmitter and receiver movement problems: The min–sum movement problem is to minimize the total moving distance over all mobile transmitters and receivers; and the min–max movement problem is to minimize the maximal moving distance among all mobile transmitters and receivers.

In this paper, we provide optimal and near optimal solutions to the bistatic radar placement and movement problem. Our contributions can be summarized as follows:

- Prove the optimal bistatic radar transmitter–receiver placement pattern.
- Prove the structure property of a minimum cost placement sequence for complete perimeter coverage.
- Propose the method to obtain the minimum cost placement sequence.
- Propose the closest point algorithm and the exhaustive search algorithm to determine target locations in the movement problem.
- Propose two algorithms to solve the min–sum and min–max problems.
- Prove two approximation bounds for our movement solutions to the optimal solutions.

The rest of this paper is organized as follows. Section 2 reviews the related work. Section 3 presents the system model and problem description. The solution to the problem of minimum cost bistatic radar placement is studied in Section 4, and Section 5 provides our solutions to the min–sum and min–max movement problem. Simulation results are presented in Section 6, and Section 7 concludes the paper.

2. Related work

Most of the previous studies on barrier coverage are based on the disk coverage model (Kumar et al., 2007; Liu et al., 2008) or the sector coverage model (Chang et al., 2012; Cheng and Tsai, 2012; Ma et al., 2012). Also, two main network scenarios have been considered: barrier coverage consisting of stationary sensor nodes (Chen et al., 2010, 2011) and mobile sensor nodes (Kong et al., 2010; Bhattacharya et al., 2009; He et al., 2013; Kong et al., 2012).

Based on the disk coverage model, Kumar et al. (2007) study the barrier coverage construction probability with randomly deployed stationary sensor nodes for two types of barrier coverage: weak barrier coverage and strong barrier coverage. Liu et al. (2008) derive the critical conditions for strong barrier coverage and propose a distributed algorithm to construct strong barrier coverage. Chen et al. (2010) propose the concept of L-local barrier coverage to guarantee that all traversing paths confined to the belt region with length L will be detected by at least one sensor. Chen et al. (2011) also introduce another type of one-way barrier coverage which only triggers an alarm when any intruder traverses the protected region from one direction. Based on the sector coverage model, Cheng and Tsai (2012) propose a distributed algorithm to construct a visual barrier with enough breadth in order to improve image quality in directional sensor networks. Chang et al. (2012) address the problem about how to find maximum visual barrier lines with minimum camera sensors in a wireless visual sensor network. Ma et al. (2012) propose an optimal algorithm to solve the problem of how to achieve full-view coverage with minimum camera sensors in the wireless camera sensor network.

Using mobile nodes can improve deployment efficiency for all kinds of coverage problems, including area coverage (Vecchio and Lpez-Valcarce, 2015; Tamboli and Younis, 2010, blanket coverage (Cheng and Savkin, 2013) and barrier coverage (Wang et al., 2009, 2011). Kong et al. (2010) propose a distributed algorithm to move mobile sensors to the boundary of protected region and construct barrier coverage surrounding the protected region. Bhattacharya et al. (2009) construct barrier coverage with the objective of minimizing the total and maximum moving distance of all mobile sensors. He et al. (2013) consider the barrier coverage construction in the scenario where the sensors are not enough to construct barrier coverage and propose two algorithms, Periodic Monitoring Scheduling (PMS) and Coordinated Sensor Patrolling (CSP), to improve the intruders detection probability. Kong et al. (2012) propose a distributed algorithm to construct K barrier coverage via mobile sensors to surround the dynamic object with the objective to maximize K and minimize the total moving distance.

Recently, coverage with radar sensors has been becoming a new research focus. Tang et al. (2013) address the point coverage problem of a bistatic radar sensor network: Given a set of points of interest, how to place M transmitters and N receivers with the objective of minimizing the maximum distance product between each point of interests and its closest transmitter–receiver pair. Gong et al. (2013a) consider the problem of how to detect a moving target from a clutter in a monostatic radar network, and propose a new *doppler coverage* concept. Yang et al. (2013) investigate the problem of how to schedule redundant bistatic radar sensors to maximize the total area coverage lifetime in a randomly deployed bistatic radar sensor network. To the best of our knowledge, the work in Gong et al. (2013b) is the most related to our work. The paper focuses on the problem of what is the optimal placement of M transmitters and N receivers on a straight line, such that the detection probability of an intrusion cross this line can be maximized. Compared with Gong et al. (2013b), the work in this paper has several distinct differences: First, the deployment scenario is much different, circle vs. line. Hence the optimal deployment solution is also much different. Second, we compute the optimal number of transmitters and receivers with the objective of minimizing total nodes cost. Third, we also