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Spread and shrink: Point of interest discovery and coverage with mobile wireless sensors

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HIGHLIGHTS

- Localized algorithm for discovery & coverage based on spread & shrink operations.
- The spread process provides coverage and preserves connectivity.
- The spread process follows a grid coverage pattern to expand.
- The shrink process removes nodes that do not provide any coverage or connectivity.

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ABSTRACT

In this paper we tackle the problem of deploying mobile wireless sensors while maintaining connectivity with a sink throughout the deployment process. These mobile sensors should discover some points of interest (PoI) in an autonomous way and continuously report information from the observed events to the sink. Unlike previous works, we design an algorithm that uses only local information and local interactions with surrounding sensors. Moreover, unlike other approaches, our algorithm implements both the discovery and the coverage phase. In the discovery phase, the mobile sensors spread to discover new events all over the field and in the second phase, they shrink to concentrate only on the discovered events, named points of interest. We prove that connectivity is preserved during both phases and the spreading phase is terminated in a reasonable amount of time. Real experiments are conducted for small-scale scenarios that are used as a "proof of concept", while extensive simulations are performed for more complex scenarios to evaluate the algorithm performance. A comparison with an existing work which uses virtual forces has been made as well. The results show the capability of our algorithm to scale fast in both discovery, coverage and shrinking phases.

1. Introduction

Observation of the physical world is a key application in many civilian (environment), military (battlefield) and industrial (structural monitoring) domain. Wireless sensor networks made these operations easier, cheaper and more accurate. Easier because wireless sensors network can use self-configuration techniques. Cheaper due to the decreasing cost of electronics. Accurate by deploying a huge number of sensors and using network connections which can provide and spread results in some instances of time. A proper placement of wireless sensors over the area of interest is a critical job since it provides accuracy and information diffusion to the network. These two requirements are the main objectives of this paper.

1.1. Problem statement

In the context of wireless sensor network, an observation area can be reduced to only some interesting points called points of interest to reduce the complexity and the cost while maintaining the accuracy. The concept of monitoring certain points or strategic locations in the sensor field instead of the whole field area reduces the costs of the deployment by reducing the number of used sensors and helps improve the coverage performance by giving

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the ability of increasing the number of covering sensors. However, discovering the points of interest needs a complete exploration of the target area.

The points of interest can be discovered thanks to mobile sensors. The discovery process implies the correct spreading of the mobile sensors all over the field of interest. Depending on the number of mobile sensors and the size of the area, some points of interest may not be discovered. However, it is important to guarantee a correct spreading of the sensors to maximize the discovered area. Once the points of interest discovered, only a proportion of the mobile sensors are useful and have to stay on the field since they cover the points of interest. It actually means that the sensors have to shrink to a smaller network.

The shrinking phase allows the useless sensors to go back to their starting point after the discovery phase. Since not all the sensors are covering a point of interest, they are not used to capture information on the field. Instead of leaving the sensors on the field, in which they are prone to damages, they could be brought back to their initial position to reduce the cost of the deployment. Some are sent over the discovered points of interest to increase the observation accuracy or used as data relays from the point of interest to the sink. Therefore, the shrinking phase is important since it can reduce the cost of deployment, increase the accuracy, and strengthen the connectivity between the nodes and the sink.

Connectivity is important throughout the process, since the discovery and coverage (with the same devices) can reduce the time needed to retrieve useful information from the point of interest. Indeed, the time is minimized between the transition from discovery to coverage if the mobile wireless network connectivity is maintained all along the deployment procedure. This is an advantage of our approach over other algorithms in the literature.

The coverage of the whole target area and the point of interest are well-known problems but separately investigated in the literature. Fan et al. [13] and Wang et al. [20] provide some rich surveys on the deployment of mobile wireless sensors to cover a given target area. Some optimal, yet centralized, strategies are described in the above-mentioned surveys. Moreover, some authors such as Razafindralambo et al. [17] have proposed some localized algorithms for the same task. The literature as described by Erdelj et al. [12] cites some important works regarding point of interest coverage. In their work, Erdelj et al. [12] assume that the points of interest are already discovered and their objective is, thus, to send some nodes to cover these points of interest. In their work, they provide an algorithm with guaranteed connectivity between the base station and each point of interest. To the best of our knowledge, combining the discovery part and the point of interest coverage part has not yet been deeply investigated in the literature. This paper fills this gap by providing an algorithm that combines discovery and coverage at the same time.

1.2. Our contribution

In this work, we propose a novel approach for adapting a network with mobile sensors to a set of points of interest. The approach is split in two phases; the spreading and shrinking process. The algorithm we propose is distributed in nature and runs on all the sensors using only the one hop information from their neighbors. The key characteristics of the approach are summarized as it follows:

- Localized algorithm for discovery and coverage process. The decisions taken by the sensors are based only on local state (single-hop neighbors).
- Spread or discovery process which preserves the connectivity all along the deployment procedure.
- The spread process follows a grid coverage pattern to expand.
- Shrink or coverage process which preserve the connectivity between the sensors that had discovered the point of interest and the data sink following the grid lines. Moreover for the non-covering sensors, the connectivity is still kept.
- A spread and shrink process that provides a permanent coverage of the point of interest once discovered.

A visual example of our approach can be seen in Fig. 1. This figure shows the time and space evolution of the sensors running the algorithm. The spreading process occurs from time 0 s to time 400 s. The shrinking process starts after the 400 s.

1.3. Related work

Our work tackles different operational issues related to point of interest coverage. Specifically, it implies exploration of the sensor field (discovery of the points of interest), monitoring of the points of interest and data gathering. Moreover, our work guarantees connectivity with the sink throughout all the phases of the approach. In this section, we analyze only the most fundamental works referring to these issues.

The coverage and monitoring of a point of interest or of an area of interest are subjects covered from both the ad-hoc, sensor and robotics community by using different approaches and by focusing on different aspects. The ad-hoc and sensor community consider devices such as sensors and actors, whose power as well as computational and execution capabilities are limited. The robotics community takes into account smarter and more powerful devices and assumes that communications do not have a basic importance in achieving the coverage of the area. They call this kind of approaches "formation control". Since the topic has been extensively treated by both the communities in recent years, we will focus on the efforts produced by the ad-hoc and sensor community, which are more relevant to our work. For a survey on robotics formation control techniques please refer to the work of Wang et al. [18].

Younis et al. [24] and Wang et al. [20], authors survey and classify strategies and techniques for node placement and movement strategies for improving network coverage, respectively. They propose to classify works according to the targeted coverage. Specifically, full coverage aims at completely covering the field by geographically distributing sensors and actors on the entire area of interest in order to continuously monitor it.

Zou et al. [27] and Wang et al. [19] use mobility of the nodes in a more extensive way, in fact they propose target localization and sensor deployment, respectively, by using virtual forces. Our approach, also, considers a large use of mobile nodes as the last two cited works, but the main difference is in the algorithm that drives the nodes movements. We do not use virtual forces to avoid limiting the mobility of nodes only to the attraction–repulsion mechanisms and, also, to provide the grid coverage approach. Moreover, we redeploy the sensors in the shrink phase to focus only on the discovered points of interest and to reduce the number of sensors involved in the network.

Cheng et al. [8] study the maximum coverage problem in complex urban scenarios. The authors provide a geometry-based coverage strategy to handle the deployment problem over urban scenarios. This work is very interesting since it considers obstacles. However, the work does not consider the shrinking phase described in this paper. We will include the constraints raised in this paper regarding mobility pattern in our future work.

It is, also, important to notice the work of Bartolini et al. [1] which describes a hexagonal tilling deployment for a complete coverage of the area of interest. We use the same tilling in our work for the discovery (spreading) process since the hexagonal tilling guarantees at the same time network connectivity and optimal