

Auto sensor deployment and local coverage-aware recovery schemes for smart environments

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Abstract

One critical issue, for a wireless sensor network (WSN) to operate successfully, is to provide sufficient sensing coverage. Define the smart sensing environment as a sensing system with the capability to sense the environment and respond properly in an automated manner. In this paper, we target on smart sensing environments and deal with heterogeneous sensors (here sensor heterogeneity is defined as sensors having different sensing ranges) equipped with actuation facilities to assist in the sensor self-deployment. A coverage-aware sensor automation (CASA) protocol is proposed to realize an automated smart monitoring network. Two centralized algorithms are included in the CASA protocol suite: enhanced virtual forces algorithm with boundary forces (EVFA-B) and sensor self-organizing algorithm (SSOA). Unlike most previous works that tackle the deployment problem only partially, we intend to address the problem from both global deployment (EVFA-B) and local repairing (SSOA) perspectives.

1.INTRODUCTION

Advances of micro-electromechanical system (MEMS), sensing technology, and wireless communication have significantly encouraged the development of WSNs in the past decade. A WSN is widely used for habitat and environmental surveillance, medical application (with the purpose of improving quality of health care), agricultural assistance, and as solutions to military problems [8], [17], [22], [23]. Several experimental test beds are also implemented to investigate various aspects of WSN-related performance issues [16], [27], [30], [32]. Imagine an indoor sensing environment, as depicted in Fig. 1a. To furnish the environment with monitoring capability, one possibility could be embedding a secret compartment under the roof, and deploying smart sensors inside the double-deck structure on the ceiling.¹ For a successful

surveillance, providing sufficient sensing coverage is essential. Manual placement of static sensors involves labor effort (reaching the ceiling to perform the planned deployment) and lacks network self-healing competence (when faulty sensors occur). Thanks to the availability of motion facilities, we consider smart sensors with mobility capability to accomplish self-deployment after an initial random placement of sensors.² Furthermore, since sensing devices are prone to errors due to energy depletions or unexpected failures, faulty sensors may occur over time, leaving monitoring voids (uncovered sensing holes) [13], [31], [34]. With the movement ability, instead of replacing faulty sensors with new ones, those smart sensors reposition themselves to restore the sensing coverage, as illustrated in Fig. 1b. According to the above descriptions, two deployment-related issues need to be addressed. First, a coverage-aware sensor deployment scheme should be developed to ensure sufficient sensing coverage. Second, in the face of sensing node failures, a sensor self-organizing mechanism needs to be devised to efficiently recover the sensing void and restore the required sensing coverage. Since local repairs generally consume less moving energy and communication overhead than a global redeployment does, the sensor self-organizing mechanism should limit the network recovery/repairing locally to effectively reduce unnecessary

1. Embedding a secret compartment under the roof is only one possible way to exhibit the deployment feasibility. The proposed algorithms can also work effectively in other environmental settings as long as the sensing behavior can be projected onto a 2D bounded area. Note that our envisioned application is to provide effective and energy-efficient sensors auto-deployment mechanisms with self-healing

capabilities for indoor/outdoor monitoring sites where labor deployment is difficult, troublesome, or hazardous.

2. We define the smart sensing environment as a sensing system which has the ability to sense the environment and react with proper responses in an automated manner, moving energy consumption. In this work, we do not intend to study the energy-conserving sensor communication behavior³ (though we try to reduce the moving energy by keeping sensors from moving far away when performing self-deployment), nor the issue of required amount of sensors to achieve certain degree of sensing coverage. Rather, given any number of sensors, we investigate the deployment-related problems and propose a coverage-aware sensor automation (CASA, which means "home" in Spanish) protocol including the aforementioned two deployment-related designs, with the objective of providing/maintaining high sensing coverage. Our ultimate goal is to realize an automated monitoring network so that detection applications of various emergency events can be practically implemented. The remainder of this paper is organized as follows. Section 2 reviews several prior research efforts and summarizes our unique contributions. In Section 3, we introduce the CASA protocol and provide the environmental assumptions made by the protocol. The proposed CASA protocol consists of two closely-related algorithms to address the sensor deployment scheme (EVFA-B) and sensor self-organizing mechanism (SSOA), respectively. Sections 4 and 5 elaborate on the detailed operations of EVFA-B and SSOA separately. Section 6 presents the performance and comparison results, while Section 7 reports our prototype of an automated monitoring network (MoNet) and demonstrates the detection capability of CASA-enabled MoNet. Finally, we draw our concluding remarks in Section 8.

2. PRIOR WORK

Depending on the target applications, earlier studies in WSNs generally focus on either outdoor large-scale environments, where planned sensor deployment is difficult, or indoor small-scale monitoring zones, where sensor deployment mechanism is feasible and beneficial. For large-scale WSNs, several works have been proposed to

address the energy conservation issue [21], [31], [36], [40], [41]. Given sufficient number of sensors randomly deployed (scattered) over the monitoring field to ensure a certain degree of redundancy in sensing coverage, those proposals design node working schedules such that sensors can rotate between active and sleep modes. The objective of those proposed working schedules (node-scheduling protocols) is to achieve energy conservation (prolonging system lifetime), while preserving reasonable sensing coverage and network connectivity. For the monitoring environments where planned sensor deployment is possible, various static deployment strategies have been introduced to enhance the surveillance coverage [11], [12], [18], [35], [37]. In this kind of research studies, one commonly considered metric is to minimize the number of sensors required to achieve a certain sensing coverage. Due to different sensor capabilities (e.g., distinct attainable sensing/detection ranges) and manufacturing expenses, this metric is sometimes transformed into minimizing/optimizing the required total device cost for those deployed sensors, making this research subject more interesting yet challenging [11], [35]. However, such static deployment involves manual sensor placement/installation, and is incapable of dynamically repairing sensing voids (uncovered areas) in the presence of unexpected sensor failures. Consequently, a number of research efforts have explored the movement-assisted sensor deployment techniques by utilizing mobile sensors to enhance the sensing coverage after an initial random placement of sensors [33], [39], [42]. With the motion facilities equipped at the sensing devices, sensors can move around to deploy themselves. Given any number of randomly placed sensors, in [42], the authors present a centralized force-guided algorithm, inspired by the disk packing theory and virtual force field concept from robotics, to establish motion paths for sensors. Assuming there exists a powerful cluster head, capable of communicating with all sensors and obtaining sensor locations, the

Fig. 1. Illustration of an automated monitoring network, and the importance of (movement-assisted) network self-healing capability to tolerate sensor faults (no need to deploy new sensors).

3. Here we mean that how to design an energy-efficient sensor communication protocol is not of

interest. However, the communication overhead (consumed energy) incurred by deployment algorithms is of concern and has been considered in our energy performance results in Section 6. proposed algorithm evaluates all attractive and repulsive forces and obtains the resultant force exerted on each sensor. The computed resultant force then directs the sensor to move to a desired position. Also utilizing mobile sensors, the authors in [33] introduce a distributed sensor self-deployment scheme. They suggest to firstly identify the coverage holes (sensing voids) based on Voronoi diagram, and then propose three algorithms (choices) to guide sensor movements toward the detected holes. However, accurate Voronoi polygon constructions are not always possible to achieve, due to unevenly distributed sensors with limited communication distances. Therefore some optimization heuristic is needed to prevent sensors from moving too far and keep a reasonable number of total movements, further complicating the deployment computations. Furthermore, since the termination condition for the Voronoi-based deployment strategy is coverage, for a monitoring environment with sensor number much larger than necessary, unbalanced sensor distribution (some areas are much more highly populated than other areas, even with an overall sensing coverage required) is likely to occur. As a result, the authors in [39] develop a scan-based movement-assisted sensor deployment (SMART) method to address the unbalanced problem. Instead of tackling the deployment problem directly, SMART focuses on sensor load balancing by using 2D scanning and dimension exchanges to achieve a balanced network state. As claimed by the authors, SMART can operate on top of existing sensor deployment schemes, and produces good performance especially for unevenly distributed WSNs. The aforementioned movement-assisted sensor deployment techniques all consider homogeneous sensors (with equal sensing/detection radius). A more recent work [7] introduces the VorLag algorithm, which takes heterogeneous mobile sensors into the deployment considerations. The proposed VorLag solution enhances traditional Voronoi-based approach by incorporating Laguerre geometry to accommodate diversity in the sensing range/radius. We observe that most previous works explore the sensor deployment problem only partially, leaving issues such as heterogeneous

sensors (with different sensing ranges) and locally recovering sensing holes (caused by sensor failures) unaddressed. However, in practice, those closely-related deployment issues should be resolved as a complete protocol set to achieve an operative WSN with high detection capability. In light of this, we investigate the movement-assisted sensor deployment subject by considering those deployment-related problems in a holistic manner. A CASA protocol suite is proposed to address the global sensor deployment scheme (EVFA-B) and sensing coverage recovery in the presence of sensor failures (SSOA). We summarize our unique contributions as follows. First, we develop the enhanced virtual forces algorithm with boundary forces (EVFA-B) based on the concept of potential

field and disk packing theory. Though sharing similar idea of virtual forces with [42], our EVFA-B deals with both the homogeneous and heterogeneous sensors, while [42] only discusses the case of homogeneous sensors, where a global distance threshold value is adopted in determining whether an attractive (with weight constant w_a) or repulsive (with weight constant w_r) force should be applied on a sensor. However, in realistic settings, where varying sensing distances are common, the distance threshold (determining the desirable sensing overlapping degree) should be selected on a node-pair basis, instead of being set globally. In addition, since the observed environment is usually in a bounded area, our EVFA-B incorporates the boundary force (with weight constant w_b) as a kind of repulsive force from the boundaries to keep sensors staying inside the monitoring area. Since the boundary force is considered as a type of repulsive force, we use the same value for w_r and w_b . In [42], no boundary force is modeled, and no specific design guidelines are available for determining suitable w_a and w_r ($\frac{1}{4} w_b$) weight constants. Motivated by the observations, we investigate and conjecture that good choices for w_a and w_r ($\frac{1}{4} w_b$) greatly depend on sensor population and monitored area dimensions, while independent of sensing radius.

3. COVERAGE-AWARE SENSOR AUTOMATION PROTOCOL

Two deployment-related mechanisms are incorporated in our CASA protocol set: EVFA-B

and SSOA. The detailed operations of respective mechanism, with the objective of enhancing/preserving/recovering the sensing coverage for a smart sensing environment, are elaborated in Sections 4 and 5, respectively.

Below

we summarize the environmental assumptions made

in this work.

(A1) There exists a powerful clusterhead responsible for performing centralized computations. All sensors are able to communicate with the clusterhead via single-hop or multi-hop wireless transmissions. (A2) Sensors have the isotropic sensing shape and the binary sensing/detection behavior, in which an event is detected (not detected) by a sensor with complete certainty if this event occurs inside (outside) its sensing radius. Both the homogeneous (having identical sensing range) and heterogeneous⁵ (having varying sensing ranges) sensors are allowed in our model. Information of respective sensing ranges is provided

4. Since heterogeneity in WSNs exists in many dimensions, here we use the adjective term "heterogeneous" to refer to a sensing model where sensors have different sensing distances/ranges.

We adopt the discrete coordination system, in which the monitoring area (sensing field) is represented by a 2D grid network. Locations of all sensors are obtained via the pre-deployed RFID platform or some existing localization technique, and constantly updated to the clusterhead.⁶ Neighboring nodes under the adopted coordination system are defined as sensors within the sensing range (r_s), which is normally much smaller than the radio communication distance (r_c). Without loss of generality, we assume that $r_c > 2r_s$ in our model. According to the derivations in [21], [41], if the radio communication range (r_c) is at least twice the sensing radius (r_s), complete coverage of a convex area implies connectivity among the working set of sensor nodes. Consequently, in this work, we only deal with the sensing coverage, and network connectivity follows accordingly.

4. ENHANCED VIRTUAL FORCES ALGORITHM WITH BOUNDARY FORCES (EVFA-B)

The concept of virtual forces is inspired

by the combined idea of potential field and disk packing theory [14], [20]. Each sensor behaves as a source giving a force to others. This force can be either positive (attractive) or negative (repulsive). If two sensors are too close, they exert repulsive forces to separate each other, otherwise they exert attractive forces to draw each other.

5. SENSOR SELF-ORGANIZING ALGORITHM

Wireless sensors are inherently unreliable. Due to sensor energy depletions or unexpected failures over time, the decreased sensing coverage deteriorates the event detection capability of a WSN. To preserve the required sensing coverage, one alternative is to perform EVFA-B (presented in Section 4) periodically for global redeployments. However, such constant global redeployment is costly in terms of communication overhead and consumed moving energy, and should be kept infrequent. Therefore, we propose the SSOA to firstly repair the sensing void (uncovered area caused by some broken sensor) by locally repositioning sensors around the sensing hole. Two issues need be addressed to realize this local recovery: selection of repairing sensors (Section 5.1) and physical movements performed by the selected sensors (Section 5.2). In case the local repairing is unable to recover the required sensing (detection) capability, SSOA then invokes EVFA-B to globally redeploy sensors.

5.1 .Local Selection of Rescue Sensors

The first challenge of accomplishing partial repair is to locally select the rescue sensors around the sensing hole. Given a sensing hole caused by some broken sensor (s_{dead}), all active sensors nearby (not necessarily the immediate neighbors of s_{dead}) can be potential candidates to perform the local repair. Theoretically, every combination of rescue sensor candidates along with various moving strategies should be examined to obtain the most desirable coverage improvement. However, this approach is intractable, and not implementable.

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