Relocation Strategies for Mobile Sensor Networks in Emergency Coverage Situations

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A Thesis

in

The Department

of

Electrical and Computer Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Science (Electrical and Computer Engineering) at

Concordia University

Montréal, Québec, Canada

November 2019

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

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Entitled: Relocation Strategies for Mobile Sensor Networks in Emergency Coverage Situations

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Electrical and Computer Engineering)

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Abstract

Relocation Strategies for Mobile Sensor Networks in Emergency Coverage Situations

Mohammadkazem Agah

The focus of this thesis is directed towards developing distributed coordination protocols for a group of agents (mobile sensors) deployed to cover an area of interest. It is assumed that sensors are subject to an alert message at any point in time, which is issued in an emergency situation. Such an emergency event is formulated as an abrupt change in the coverage priority of specific regions in the field. In the normal situation, a protocol is used to move the mobile sensors in the plane in such a way that the overall sensing coverage is increased. Then, as soon as an alert message is issued, sensors that receive the information communicate with their neighbors to inform them of the message. An appropriate number of sensors are subsequently tasked to further improve the coverage of the specified area by adjusting their positions iteratively to increase the coverage of the alert area. Two types of algorithms are developed, where the first one is mainly focused on the alert area coverage, and the second one aims to also cover the rest of the field as much as possible. The algorithms are Voronoi-based, and are guaranteed to increase the desired sensing coverage at each iteration. Some examples and comparative results are provided to demonstrate the effectiveness of the proposed

algorithms.

To my parents

for their love and sacrifice

Acknowledgements

This work would not be possible without the guidance and the advice of some people.

First and foremost, I would like to express my deep gratitude to my exceptional supervisor, Dr. Amir G. Aghdam for the opportunity he gave me to be a member of his research team which was an unforgettable experience for me. I am greatly thankful for his continuous motivation, experience and helpful guidance.

I would like to offer my sincerest appreciation to Dr. Hamid Mahboubi who shared his invaluable knowledge in the completion of this dissertation.

I have great pleasure in acknowledging my gratitude to my colleagues and friends, Sepehr Radmannia, , Kian Gheitasi, Mohsen Ghaderi, Amir Pirhadi, Hamed Molaei, Boshra Arghavani, David Buzorgnia, Jalal Arabneydi and Milad Esmaeilpour for their support and encouragement.

It would be inappropriate if I omit to mention the biggest source of my strength, my beloved parents, brother and sister. I thank them for putting up with me in difficult moments.

Table of Contents

List of Figures

Chapter 1

Introduction

1.1 Motivation

There has been a growing interest recently in the application of wireless sensor networks (WSNs) [1], [2]. Such applications include, for example, environmental monitoring, target tracking, traffic network control, and biomedical engineering, to name only a few [3], [4], [5] and [6]. In coverage problem, in particular, it is desired to place a group of sensors in an area of interest in such a way that it is covered as much as possible (e.g., any activity in the area is monitored) [7]. Various sensor deployment strategies are proposed in the literature for both static and mobile WSNs.

In developing an efficient WSN, many practical issues need to be taken into consideration. For instance, the network lifetime and connectivity are important factors that can significantly affect the coverage performance [8], [9]. Different definitions are provided in the literature for the network lifetime [10]. In this thesis, in accordance with [11], the network lifetime is defined as the time it takes for the first sensor to run out of energy. In static WSNs, there are two main sources of energy consumption: sensing and communication. In mobile WSNs, on the other hand, the dominant source of energy consumption is sensor movement [12]. Thus, in the development of energy-efficient coverage algorithms for mobile WSNs, it is important to use an effective relocation strategy for the sensors.

In some mobile WSN applications, the sensors are initially deployed randomly, e.g., by dispersing them from an aircraft [13]. The sensors are then follow a prescribed relocation strategy to fill the coverage holes in the field. In some other applications, a group of mobile sensors are used to further improve the coverage performance in an existing static WSN [14]. In all of these applications, the effectiveness of the strategy depends on important factors such as the size of region, number of sensors, their sensing range and other capabilities. There are also important trade-offs in terms of coverage performance and network lifetime that need to be taken into account [15], [16].

1.2 Related work

In this section, some of the existing results for coverage maximization in a WSN are reviewed.

Most of the existing sensor movement strategies in the literature use one of the following three types of techniques: coverage pattern [17], [18], [19], grid architecture [20], [21], and virtual forces [22], [23]. In [17], a novel sensor deployment algorithm is presented, called the adaptive triangular deployment (ATRI) algorithm, for large-scale unattended mobile sensor networks. The ATRI algorithm helps to maximize coverage area and minimize coverage gaps and overlaps by adjusting the deployment layout of nodes close to equilateral triangulation, which is proven to be the optimal layout "for maximum no-gap coverage". Two related deployment problems, namely sensor dispatch and sensor placement, are considered in [18]. The solutions to the dispatch problem include a centralized and a distributed method. The authors in [19] presents the efficient obstacle-resistant robot deployment (ORRD) algorithm, which involves the design of a node placement policy, a serpentine movement policy, obstacle-handling rules, and boundary rules. In this robot deployment mechanism, unpredicted obstacles with regular or irregular shapes are also considered. In [20], a generic framework is considered for the optimal mobile sensor redeployment problem in WSNs. To this end, the area to be covered is partitioned into a few grids, and the gap of each grid is defined as the difference between the actual number of sensors in the grid and the desired number of sensors there. Then, the mobile sensor redeployment problem is formulated as an optimization problem with some constraints. A centralized algorithm is proposed in [21] to minimize the total traveling distance of sensors for covering a sensing plane. Various strategies are then investigated to reach a balanced state by using scan and dimension exchange. The authors in [22], present a virtual centripetal force-based coverage-enhancing algorithm for Wireless multimedia sensor networks (WMSNs) by introducing a proper force model and defining sensor's mass, showing the overlap between sensors. This helps efficiently shut off redundant sensors and enhance coverage factor. In [23], two distributed protocols, namely, the basic protocol and virtual movement protocol, are proposed for controlling the movement of sensors to achieve target coverage. In both movement protocols, three algorithms, VEC, VOR, and Minimax, are proposed to calculate the target locations if coverage holes exist.

A distributed self-relocation algorithm on the basis of average relative position between pairs of sensors is studied in [24]. This technique consists of three phases to relocate the randomly deployed sensors and perform a sensing range adjustment using Voronoi diagram so that an optimized coverage is achieved with minimum consumption of energy. The authors in [25], studied the problem of maintaining sensing coverage by keeping a small number of active sensor nodes and a small amount of energy consumption in a wireless sensor network. They consider a large number of sensors with adjustable sensing radius that are randomly deployed to monitor a target area. In this article, A novel coverage control scheme based on elitist non-dominated sorting genetic algorithm (NSGA-II) is proposed in a heterogeneous sensor network and by devising a cluster-based architecture, the algorithm is applied in a distributed way.

In most of the above-mentioned sensor deployment algorithms, it is assumed that the coverage priority for different points in the field is uniform which is in contrast with many real-world problems. The sensor deployment problem in a nonuniform field is considered in [26], [27], [28]. In [26], coordination algorithms are provided for sensor deployment and coverage, where a class of aggregate objective functions is also considered with regard to the geometry of the Voronoi partitions and proximity graphs. In [28], a class of area-constrained locational problem investigated and two distributed coordination algorithms are introduced where a group of robots seeks to optimize a notion of environmental coverage by partitioning the space into regions that have a prespecified area. New distributed deployment strategies are introduced in [29] to increase coverage in a network of nonidentical mobile sensors with a prescribed priority function for the sensing field. The coverage priority of different points in the field is assumed to be specified by a priority function which demonstrates the coverage importance of each point in the network. The MW-Voronoi diagram is then used to find coverage holes and move the sensors accordingly to minimize them, while taking into account the coverage priority of different points in the field. In this work, three algorithms are developed: maximum weighted vertex (MWV), maximum weighted point (MWP), and maximum distance weight (MDW). The main idea behind the proposed algorithms is to move each sensor iteratively in such a way that its weighted coverage increases. [30] proposes efficient schemes to increase sensing coverage in a network composed of both mobile and static sensors. In this work, new distributed sensor deployment strategies are introduced for a network consisting of both static and mobile sensors. The multiplicatively weighted Voronoi (MW-Voronoi) diagram is utilized to discover the coverage holes, where the weight assigned to each mobile sensor is proportional to its sensing radius. In the proposed strategies, namely, farthest weighted vertex (FWV) and Max-area, each static sensor transmits its sensing radius and position to all mobile sensors. Every mobile sensor then assigns a proper virtual weight to each point in the plane on the basis of received information. The algorithms are subsequently performed iteratively to compute the destination point for each mobile sensor.

1.3 Thesis Contributions

Our main coverage problem investigated in this dissertation consists of two parts. The first part is concerned with a mobile sensor network to increase the coverage of a specified zone in the field where the sensors are connected to the neighbors. To this regard, some distributed iterative algorithms are proposed to guide the sensors toward the insecure zone. In each iteration, a Voronoi diagram constructs for partitioning the network. Then, each sensor computes the next position and if the movement conditions (which lead to increasing the coverage of alert area) are satisfied, the sensor moves physically toward its destination. It is shown that under these algorithms the network converge to a steady state. Moreover, Some important characteristics of the network like convergence rate and energy consumption are discussed.

The second part studied in this dissertation is concerned with finding a method for mobile sensor networks to decrease the coverage holes existed in the network. In fact, covering the other parts of the network is our second priority. To reach this goal, we assign a pre-specified threshold for the coverage of alert area. Once the coverage factor of this area exceeds the threshold, another algorithm would apply to each of the other sensors to move them in such a way that minimizes the coverage holes. As a result, each sensor that is not covered the alert zone, discovers the holes located inside its corresponding local area and consequently it is going to move toward them to be covered. Under this technique, the local coverage holes decreases. Furthermore, the effectiveness of proposed methods for network coverage are analyzed. These methods are also compared based on some important criteria.

1.4 Thesis Layout

The structure of the thesis is as follows:

- **Chapter 1** includes the motivation and related work for the study, and outlines the contributions of the thesis.

- **Chapter 2** studies a new problem to increase the coverage of an insecure zone inside the field. New techniques are proposed to improve alert area coverage more efficiently. The methods are mainly concerned with the intersected area and distances of each sensor and the alert zone. The main feature of these algorithms is that the sensor movement is performed iteratively. Some examples are provided to demonstrate the efficacy of the results.

- **Chapter 3** investigates the problem of decreasing the coverage holes in the plane after monitoring the insecure area in mobile sensor networks. The network consist of alert area and other parts. It is ideally desired to detect the problem inside the alert area and then to avoid loosing the coverage in the field. Three methods are introduced for considering the coverage of all parts of the network. The main idea behind these algorithms is to move each sensor iteratively in such a way that its local coverage is increased.

- **Chapter 4** summarizes concluding remarks as well as the possible future research directions in this area.

Chapter 2

Alert Area Coverage in Wireless Mobile Sensor Networks

This paper presents distributed coordination protocols for a group of agents (mobile sensors) deployed to cover an area of interest. It is assumed that sensors are subject to an alert message at any point in time. In the normal situation, a protocol is used to move the mobile sensors in the plane in such a way that the overall sensing coverage is increased. Then, as soon as an alert message is issued, sensors that receive the alert information communicate it with their neighbors to inform them of the message. An appropriate number of sensors are subsequently tasked to further improve the coverage of the specified area by adjusting their positions iteratively. The algorithms are Voronoi-based, and are guaranteed to increase the desired sensing coverage at each iteration.

Some examples and comparative results are provided to demonstrate the effectiveness of the proposed algorithms.

2.1 Introduction

Recent growth in micro-electro-mechanical systems (MEMS) technology and digital electronics has enabled the development of low-power mobile sensors that can communicate in short distances. There has been increasing interest in the literature in the coordination of wireless sensor networks due to their applications, e.g., in health-monitoring, object tracking and environmental assessment [31], [32], [33]. Mobile sensor networks consist of wireless nodes capable of moving in different directions and communicating with other sensors within their sensing range. In this type of network, it is desired to achieve a global objective such as target tracking [33] or coverage [23] in a cooperate fashion [34].

The Voronoi diagram is a tessellation into a set of polygons, each associated with a so called "generating point" in the plane. The Voronoi partitioning is an effective tool for the development of control algorithms for multi-agent systems to achieve various global objectives such as coverage [35]. A Voronoi-based multi-objective evolutionary algorithm is used in [36] to maximize the network lifetime and coverage simultaneously. The authors in [37] propose an approach to estimate and reconstruct the boundary of a region with mobile agents in a Voronoi diagram. Vector-based and Voronoi-based algorithms are proposed in [23] for controlling the movement of sensors to find a suitable position such that the covered area is increased. In [38], a Voronoi-based strategy is proposed for maximizing the coverage in a mobile sensor network. This is achieved by using a gradient-based nonlinear optimization approach to find a target point for every sensor such that the covered area increases as much as possible.

In most of the aforementioned sensor deployment protocols, the coverage priority is assumed to be the same in different parts of the area. In some practical applications, however, certain parts of the region may have a higher priority as far as coverage is concerned. The sensor deployment techniques in a non-uniform field (in terms of coverage priority) are introduced in [26], [28], [38], [29] but the formulations provided in in these papers cannot address the case where the coverage of a specific region in the sensing field becomes important at certain point in time.

In the present work, distributed protocols are introduced to relocate a group of mobile sensors in a field such that the coverage in a specific region of interest (e.g.. due to an emergency situation) is further increased. First, the field is partitioned into the Voronoi regions, and then each sensor assigns an appropriate weight to every point in the plane based on the information it receives from its neighbors. The key idea is to iteratively relocate the sensors in such a way that the coverage of the points within the region of interest increases. Note that once a sensor receives some information about the region of interest, it informs its neighboring sensors, and they subsequently move towards that region, using some approaches similar to the maximum weighted vertex strategy [29]. Simulations confirm the efficacy of the proposed sensor relocation algorithms.

The reminder of this paper is organized as follows. In Section 2.2, some background information concerning the Voronoi diagram and its important properties are briefly discussed. Then in Section 2.3, the problem is formulated and useful notations are given. The main contributions of the paper are provided in Section 2.4, where new distributed sensor relocation algorithms are introduced. In Section 2.5, the convergence properties of the proposed algorithms are studied, and finally conclusions are drawn in Section 2.6.

2.2 Preliminaries

Consider a set of n nodes in the plane denoted by $S = \{S_1, S_2, ..., S_n\}$, and define $\mathbf{n} := \{1, 2, ..., n\}$. Divide the field into n regions such that each region contains only one node, called its generating node, and that the closest node to any point in each region is its generating node. The diagram obtained by the partitioning described above is called a *Voronoi diagram*, and each region, which is, in fact, a polygon, is referred to as a *Voronoi Polygon*. The Voronoi partitioning has applications in a wide variety of areas in science and engineering, e.g., in modeling biological structures, correlating sources of infections in epidemics, and target tracking in mobile sensor networks [39], [40], [41].

Each Voronoi Polygon Π_i in this diagram can be mathematically described as:

$$\Pi_i = \left\{ Q \in \mathbb{R}^2 \mid d(Q, S_i) \leq d(Q, S_j), \forall j \in \mathbf{n} - \{i\} \right\} \tag{2.1}$$

for any $i \in \mathbf{n}$, where $d(Q, S_i)$ denotes the Euclidean distance between the point Q and the node S_i.

Definition 2.1. Any pair of nodes whose Voronoi polygons share an edge are said to be *neighbors*.

The first step in constructing the Voronoi diagram is to draw the prependicular bisector of any segment connecting a node to each one of its neighbors. The smallest region generated by these bisectors which includes node i is the i-th Voronoi polygon.

Consider now a sensor network modeled by a Voronoi diagram wherein each node represents a sensor. From the mathematical description of the Voronoi diagram, any phenomenon in the i-th Voronoi region which is not detected by sensor S_i cannot be detected by other sensors in the network either. Fig. 2.1 shows an example of a Voronoi diagram with 10 polygons and their generating nodes.

2.3 Problem Formulation

Given a set of n mobile sensors randomly placed in a 2D plane, let the corresponding Voronoi diagram be denoted by $\mathcal{D}$. Denote also the position of sensor S_i by P_i, and its

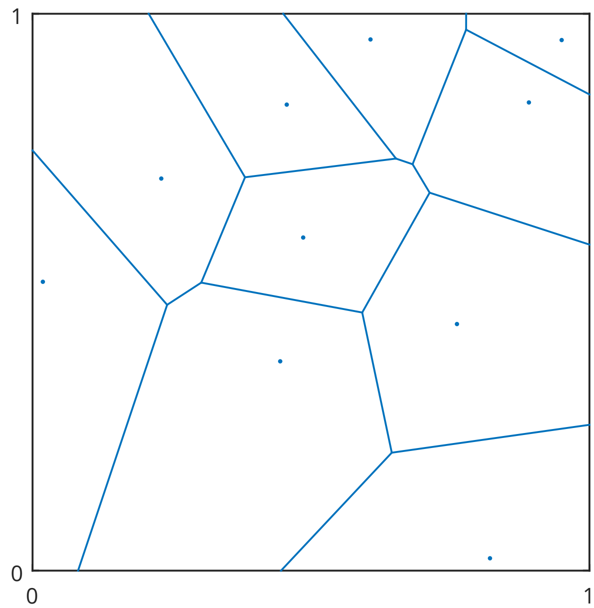


Figure 2.1: An example of a Voronoi diagram with 10 generating nodes depicted by blue dots

Voronoi polygon by Π_i, for any $i \in \mathbf{n}$. It is assumed that all sensors have a disk-shaped sensing domain and the same sensing capabilities. Assume also that at some point in time, the sensing coverage at certain area in the field may become more important (due, for example, to an unpredictable emergency situation). At that time, the sensors in a sufficiently close distance from that area (neighboring sensors of alert area) will receive an alert signal, which they can share with their neighboring sensors. The objective is to relocate the sensors in the field such that the coverage of the Voronoi region of the alert sensor at the initial sensors configuration, which will hereafter be referred to as the *alert area*, increases as much as possible.

Assumption 2.1. *It is assumed in this work that the communication graph of the mobile sensors in the network is connected. Consequently, each sensor can receive information* *of other sensors and localize itself in the plane.*

In the sequel, two definitions are presented which point out the coverage of alert area by mobile sensors.

Definition 2.2. Consider a mobile sensor S_i, $i \in \mathbf{n}$, with the sensing radius r, and let the Voronoi polygon of the alert sensor right before the alert signal was generated be Π_f. The intersection of the region Π_f and the sensing disk of sensor S_i, which, by assumption, is a circle of radius r centered at P_i, and is denoted by $C(P_i, r)$, is called the *local coverage of the alert area* of the i-th sensor, and is denoted by β_i. Moreover, the intersection of the alert area and the union of the local coverage of the alert areas of all sensors is referred to as the *total coverage of the alert area*, and is denoted by β.

Definition 2.3. Part of the *local coverage of the alert area* of the i-th sensor which is only covered by sensor S_i is referred to as the *local exclusive coverage of the alert area* of the i-th sensor. Denote this area by λ_i, and the intersection of the alert area and the union of all local exclusive coverage of the alert areas by λ, i.e., $\lambda = \sum_{i=1}^{n} \lambda_i$. This intersection area will hereafter be referred to as the *total exclusive coverage of the alert area.*

2.4 Deployment Protocols

Two deployment strategies are presented in this section for a network of mobile sensors subject to an alert signal as described earlier. Immediately after the alert signal is generated, the alert sensor broadcasts its position and Voronoi polygon information to its neighboring sensors and these sensors also transmit information to their neighbors. Then, every mobile sensor assigns an appropriate weight to different points in the plane in accordance with the information collected from the other sensors. Assume that the density (weight) function $\phi(q)$ is given over the field in order to determine the relative coverage priority of different points in the plane. The weight function is used to find the next potential location of each mobile sensor inside its current polygon.

Definition 2.4. Let the relative importance of coverage in different points be represented by a positive weight function $\phi(.)$. The integral of this function over the intersection of the region Π_i and circle $C(P_i, r)$ is called the *i-th local weighted coverage*, and is denoted by $C_{w,i}$. The mathematical characterization of the i-th local weighted coverage is as follows [29]:

$$C_{w,i} = \int_{\Pi_i \cap C(P_i,r)} \phi(q)dq, \quad i \in \mathbf{n} \tag{2.2}$$

2.4.1 Method 1: Distance-based Weight Function

For any point q in $\mathcal{D}$, the weight function $\phi(q)$ in this method is a decreasing function of the distance between q and the alert sensor as follows:

$$\phi(q) = \exp^{-\alpha(q_1 - x_f)^2 - \alpha(q_2 - y_f)^2} \tag{2.3}$$

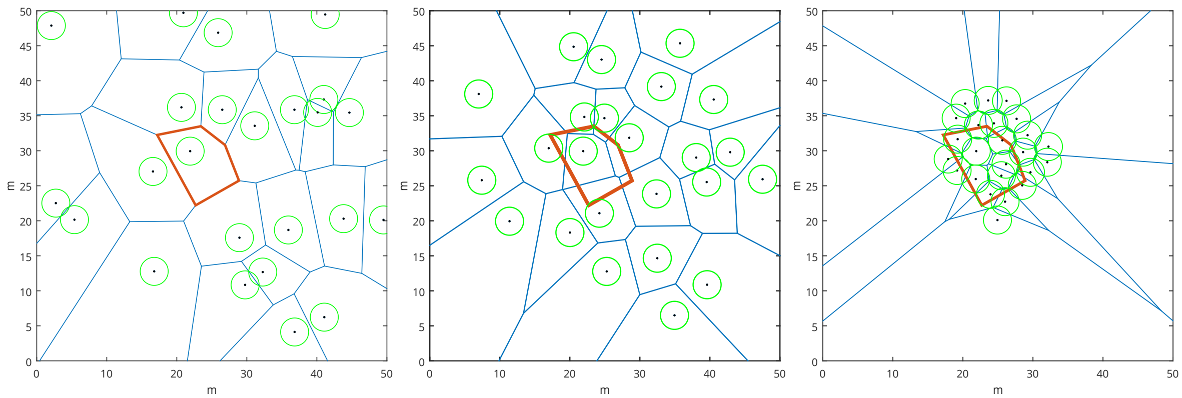
where $P_f = [x_f, y_f]^T$ denotes the location of the alert sensor and α is a prescribed constant value. Algorithm 1 is introduced to increase the coverage of the alert area as much as possible, once an alert signal is issued. It is shown later in Theorem 1.

Algorithm 1 Increasing the Alert Area Coverage

1) *Communication*: Every sensor transmits its location information to its neighbors and receives the same information from them.
2) *Voronoi diagram*: Every sensor constructs its Voronoi polygon using the information received from its neighbors.
3) *Coverage calculation*: Every sensor obtains its local coverage of the alert area and local exclusive coverage of the alert area.
4) *Next location*: Each sensor computes its destination point in its Voronoi polygon based on the Maximum Weighted Vertex (MWV) deployment strategy [29].
5) *Movement conditions*: For any sensor with a nonzero local coverage, if the local coverage of the alert area and local exclusive coverage of the alert area both increase by a certain percentage by moving to the new position, it moves there; otherwise, it remains in its current location. For any other sensor, if by moving to the new position its distance with the alert area Π_f decreases by a certain percentage, it moves there; otherwise, it remains in its current position.
6) *Termination condition*: If at least one sensor moves to a new location, the algorithm repeats from step 1; otherwise, it is terminated.

Under Algorithm 1, the total coverage increases and the algorithm converges in finite time. Note that under the MWV deployment strategy (used in step 4 of Algorithm 1), sensor S_i moves toward the vertex with highest weight of the i-th polygon denoted by $V_{i,m}$. In accordance with this deployment strategy, when the alert message is received by a sensor, it finds the vertex with highest weight in the corresponding polygon, and if the aforementioned movement conditions are satisfied, the sensor moves toward that vertex until it is covered.

Example 1. Consider a group of 24 mobile sensors deployed in a 50m by 50m flat space to fulfill the coverage task. The sensing radius r and coefficient α are 2m and 0.4, respectively. Three snapshots of the sensor network for this example are depicted in Fig. 2.2, where each sensor is shown by a black point with a circle around it, representing its sensing disk. Fig. 2.2(a) shows the initial positions of the sensors along with their Voronoi polygons, where the thick orange polygon indicates the alert area. The initial coverage factor inside the alert area (which is defined as the ratio of the covered area inside the polygon to its total area) is 16.87%; after the first iteration of Algorithm 1 it increases to 21.38%, as depicted in Fig. 2.2(b), and after the final iteration it reaches 95.33%, as shown in Fig. 2.2(c). This significant improvement in the coverage of the alert area demonstrates the effectiveness of the proposed algorithm.



(a) (b) (c)

Figure 2.2: Three snapshots of the sensor network of Example 1 along with the corresponding Voronoi diagrams. 2.2(a) The initial network configuration, with the thick orange polygon indicating the alert area; 2.2(b) network configuration after the first iteration of Algorithm 1, and 2.2(c) network configuration after the final iteration.

2.4.2 Method 2: Binary Weight Function

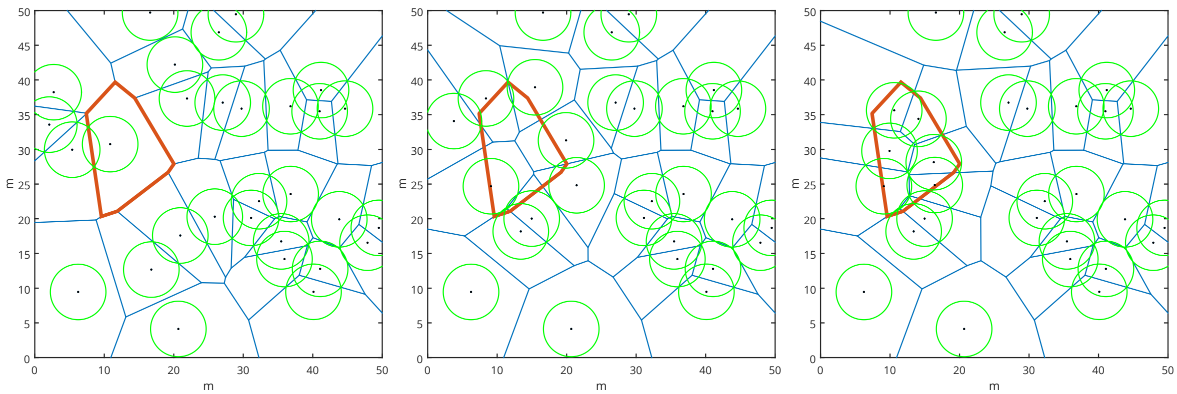
In this method, the weight of any point inside the alert area is equal to 1, and that of any point outside the alert area is equal to 0, i.e.:

$$\phi(q) = \begin{cases} 1 & q \in \Pi_f \\ 0 & q \notin \Pi_f \end{cases} \tag{2.4}$$

Then, the iterative algorithm in [29] is utilized to increase the coverage of the alert zone. Each iteration in this algorithm includes four phases. In the first phase, every sensor transmits its coordinates to the neighbors and receives similar information from them, and constructs its Voronoi polygon subsequently. Then, in the second phase, each sensor finds its destination point in its Voronoi polygon based on the above-mentioned algorithm with the binary weight function 2.4. When the new target location is determined, the weighted coverage area of each polygon is computed in the third phase. If this value is greater than the previous local weighted coverage area, then the sensor moves to the new destination; otherwise, it remains in its current location. Finally in the last phase, the algorithm terminates if there is no sensor in the network whose local weighted coverage is increased by a prescribed percentage. Note that this algorithm also uses the Maximum Weighted Vertex (MWV) strategy [29] to find the destination point for each sensor.

Example 2. In Fig. 2.3 an operational example can be seen. In this example, 30 mobile sensors are randomly deployed in a $50m$ by $50m$ flat space as shown in Fig. 2.3, and the sensing radius of every sensor is $4m$. From the configuration of mobile sensors in this figure, it can be observed that the coverage of the alert area increases in the three snapshots. In fact, the coverage of alert area increases from 31.70% in the initial round to 99.76% in the final round.

Theorem 2.1. *Let a set of n mobile sensors be randomly placed in a field in the $2D$ plane and a set of m mobile sensors which are intersected with the polygon of the alert sensor (i.e. $\beta_i > 0$). Let the positions of the m mobile sensors be denoted by $P = \{P_1, P_2, ..., P_m\}$ with the corresponding Voronoi regions $\Pi = \{\Pi_1, \Pi_2, ..., \Pi_m\}$. Assume*



(a) (b) (c)

Figure 2.3: Configurations of the sensors and the corresponding Voronoi diagrams in three snapshots under the second method. 2.3(a) Initial coverage; 2.3(b) coverage after the first round, and 2.3(c) final coverage

the sensors move to new positions $P' = \{P'_1, P'_2, ..., P'_m\}$ *with the corresponding Voronoi regions* $\Pi' = \{\Pi'_1, \Pi'_2, ..., \Pi'_m\}$ *such that* $P'_i \neq P_i$ *for all* $i \in \mathbf{M}$*, where* $\mathbf{M}$ *is a non-empty subset of* m *sensors. If the local coverage area and local exclusive coverage area w.r.t.* P'_i *in the initial constructed Voronoi region of alert sensor* Π_f *is greater than the local coverage area and local exclusive coverage area w.r.t.* P_i *in* Π_f *(i.e.* $\lambda'_i > \lambda_i$ *and* $\beta'_i > \beta_i$*) for all* $i \in \mathbf{M}$*, then the total coverage in the insecure area increases.*

Proof. In this part, we utilized Mathematical induction technique for m (intersected sensors) with the alert area to prove this theorem.

At the first step, it is shown that the theorem holds for the base case ($m = 1$):

$$\bigcup_{i=1}^{m} \beta_i = \beta_1 \tag{2.5}$$

Since the local coverage increases for each mobile sensor ($\beta_i' > \beta_i$), It is straightforward that the theorem holds for $m = 1$.

At the next step, Suppose the theorem holds for all values of m up to some $k \geq 1$:

$$\bigcup_{i=1}^{k} \beta_i' > \bigcup_{i=1}^{k} \beta_i \tag{2.6}$$

Let $m = k + 1$. We can define the overall coverage area as follows:

$$\bigcup_{i=1}^{k+1} \beta_i = \bigcup_{i=1}^{k} \beta_i + \lambda_{k+1} \tag{2.7}$$

Let the set of $k+1$ mobile sensors is defined by $S = \{S_1, S_2, ..., S_{k+1}\}$ and $\Delta\beta$ be the set of new points which will be covered by all sensors except S_{k+1} after their movements:

$$\Delta\beta = \bigcup_{i=1}^{k} \beta_i' - \bigcup_{i=1}^{k} \beta_i \tag{2.8}$$

There are two possibilities that are described below:

Case 1: The set of new points and local exclusive coverage area of S_{k+1} are disjoint:

$$\lambda_{k+1} \cap \Delta\beta = \varnothing \tag{2.9}$$

In this case, S_{k+1} does not affect other sensors' configuration and from (2.6) one can conclude that:

$$\left[\bigcup_{i=1}^{k} \beta_i'\right]_N > \left[\bigcup_{i=1}^{k} \beta_i\right]_N \tag{2.10}$$

It should be noted that $\left[\bigcup_{i=1}^{k}\beta_i\right]_N$ presents overall covered area by k sensors in the new configuration ($k+1$ sensors are placed in the network).

Case 2: It is assumed that local exclusive coverage area of S_{k+1} is intersected with $\Delta\beta$. In this case, the network might face two possible scenarios:

Scenario 1: In this scenario, there are some points in $\Delta\beta$ that are not belong to λ_{k+1}:

$$\Delta\beta \nsubseteq \lambda_{k+1} \tag{2.11}$$

So, it can be written:

$$\left[\bigcup_{i=1}^{k}\beta_i'\right]_N > \left[\bigcup_{i=1}^{k}\beta_i\right]_N \tag{2.12}$$

Scenario 2: Local exclusive coverage of sensor S_{k+1} would cover all the points belong to $\Delta\beta$:

$$\Delta\beta \subseteq \lambda_{k+1} \tag{2.13}$$

Based on the movement conditions, the local exclusive coverage area for a moving sensor (λ_i) increases. Therefore, none elements of $\{S_1, S_2, ..., S_k\}$ moves to the next location.

According to this theorem, the local exclusive coverage area for every mobile sensor increases in each iteration:

$$\lambda_{k+1}' > \lambda_{k+1} \tag{2.14}$$

According to this theorem, at least one sensor moves to the next position inside the alert area as far as the algorithm is not terminated. If sensor S_{k+1} moves to its destination, from (2.14) it can be said that its local exclusive coverage area in the alert zone increases; otherwise it does not move to the next location and it means that there is no moving sensor in the network which contradicts the fact that the algorithm is not stopped.

In overall coverage area equation (2.7), there are two terms that at least one of them increases in all above mentioned cases and scenarios.

Finally, one can conclude that:

$$\left[\bigcup_{i=1}^{k}\beta_i'\right]_N + \lambda_{k+1}' > \left[\bigcup_{i=1}^{k}\beta_i\right]_N + \lambda_{k+1} \tag{2.15}$$

or equivalently:

$$\bigcup_{i=1}^{k+1}\beta_i' > \bigcup_{i=1}^{k+1}\beta_i \tag{2.16}$$

Hence, the theorem holds for $m = k+1$. By the principle of mathematical induction, the theorem holds. It means that the total coverage area increases in each iteration under the proposed deployment scheme.

■

Theorem 2.2. *The proposed algorithm is convergent.*

Proof. The proof is similar to the proof of Theorem 1 in [34]. ■

2.5 Comparative Results

Example 3. In this example, the proposed methods are applied to a 50m $\times$ 50m field. It is desired to evaluate and compare the performances of the proposed techniques. The simulations are carried out for different number of mobile sensors n = 12, 20, 28, 36, and the average results of 20 simulations with random initial positions are displayed in Fig. 2.4, which provides the number of iterations versus the number of sensors. The termination condition considered in these simulations is when the local coverage increment for none of the sensors whose coverage circle overlaps with the alert area and the distance decrement of none of the other sensors to the alert area is more than 1%. It can be seen from this figure that the number of required iterations in the second method is less than that in the first method.

One of the important aspects of assessing efficiency of sensor deployment methods is the energy consumption of the sensors. The major sources of energy consumption in mobile sensors are the traveling distance and the number of stopping times. Fig. 2.5 demonstrates the average traveling distance of mobile sensors for different number of sensors (similar to the previous figure, the average results obtained from 20 simulations with random initial positions are presented here). It can be observed from this figure that the average moving distance increases with the number of sensors under the first method but does not change much under the second method.

Fig. 2.6 demonstrates the total number of sensor movements versus the number

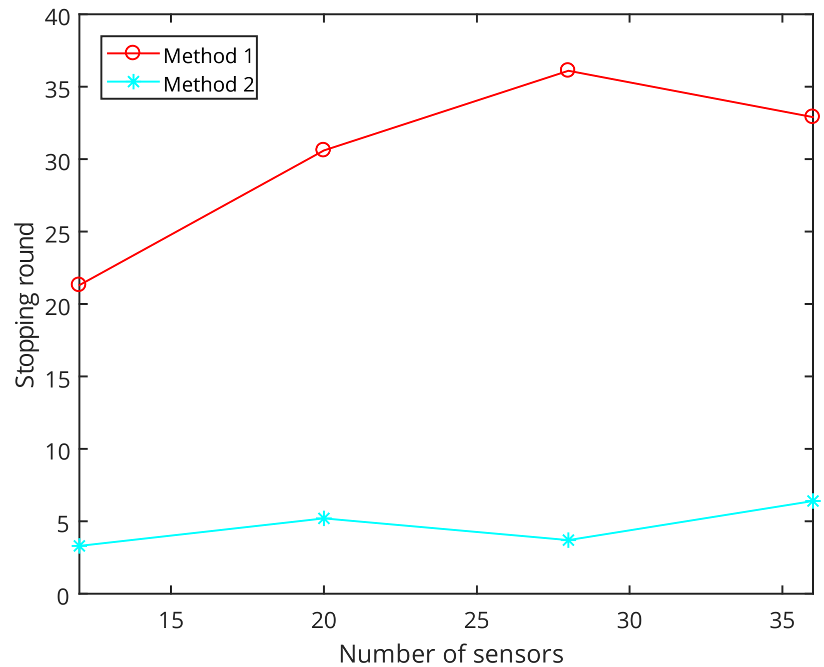


Figure 2.4: The number of required iterations to reach the termination condition for different number of sensors using the proposed techniques.

of sensors. The figure shows that the number of movements is much more dependent on the number of sensors in the first method. This is due to the fact that most of the sensors move toward the alert area under the first method but only a few of them which are close to the alert area move toward it under the second method. As a result, the number of movements and traveling distance by the mobile sensors are smaller in the second method. Thus, one can conclude that the second method outperforms the first one in terms of energy consumption. For completeness, the coverage factor of the alert area is also depicted in Fig. 2.7, which shows that the coverage performance of the first method is better than the second method.

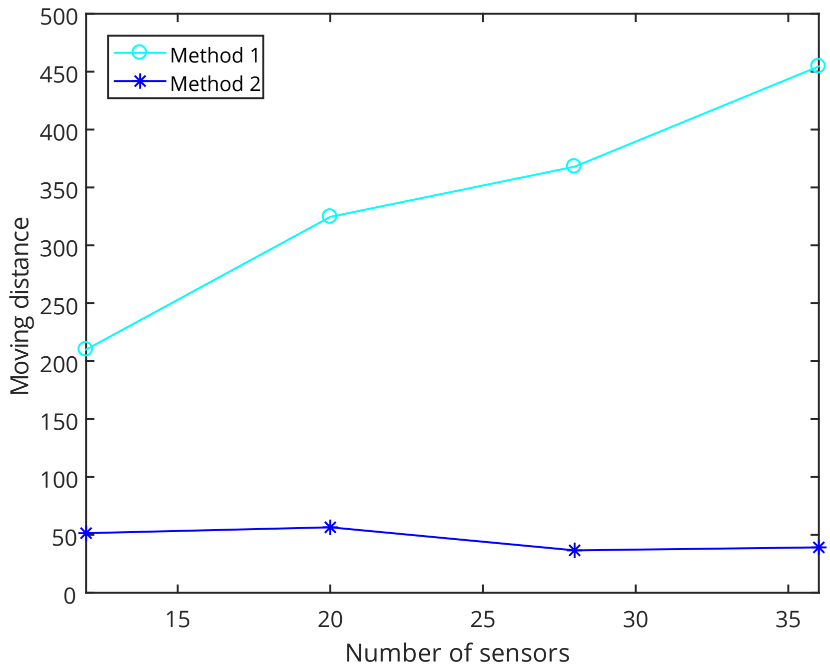


Figure 2.5: Average moving distance for different number of sensors, using the proposed methods.

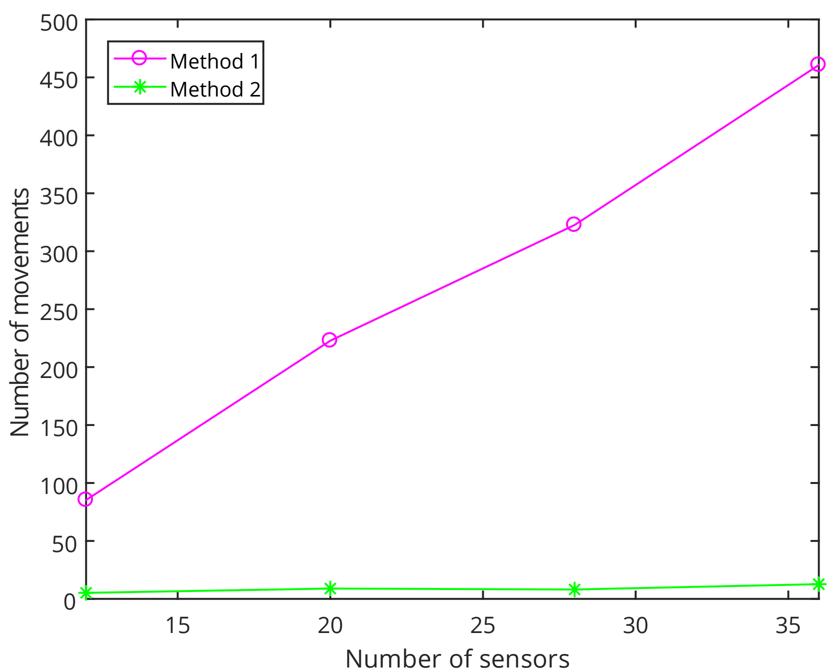


Figure 2.6: Number of movements for different number of sensors, using the proposed methods.

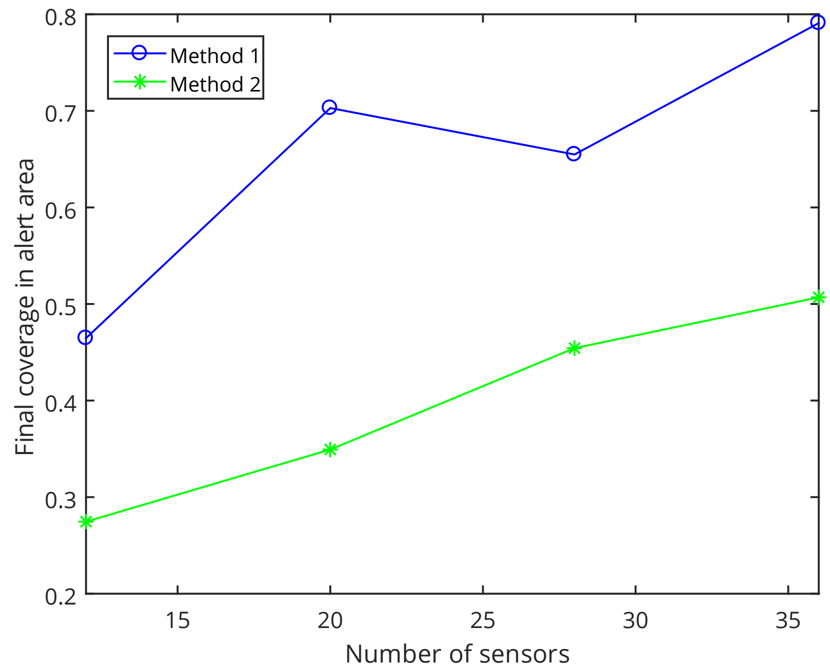


Figure 2.7: Coverage factor of the alert area for different number of sensors, using the proposed methods.

2.6 Conclusions

In this article, iterative algorithms are introduced for a network of mobile sensor. Under the proposed strategies, every sensor utilizes available information from neighbors to find the proper position inside its corresponding Voronoi polygon. The objective of this method is to increase the coverage of an insecure area in a short period of time. There are two main approaches for applying these protocols to the network. Firstly, decreasing distance between each sensor and the alert zone and increasing the overlapped area among the sensing disk of all sensors and the alert area for the first method. Secondly, increasing local weighted coverage of every sensor for the second method.

Finally, examples are presented to show the efficacy of the proposed strategies.

Chapter 3

Self-deployment Algorithm for coverage Improvement in an alert area and other parts of the field in mobile sensor networks

This chapter investigates a distributed deployment problem of mobile agents. The network consists of an arbitrary number of sensors that wish to cover the coverage holes in the presence of failure. It is assumed that every sensor constructs its Voronoi polygon using the received information from the neighbors. The proposed solutions calculate the location of sensors iteratively, based on the desired area for covering in the target plane and then each sensor moves in a proper direction to increase the coverage inside the alert area and rest of the field. Since the main objective of these strategies is covering the alert zone, a mobile sensor moves toward this insecure area at the beginning and afterward it is going to compensate the coverage holes within its Voronoi region. Examples are provided to demonstrate the efficacy of the proposed strategies.

3.1 Introduction

Recently, there has been an increasing interest in the applications of Multi-agent systems. Some examples of recent applications of this type of network include traffic surveillance,intrusion detection and environmental monitoring, to name only a few [42], [43] and [44]. In particular, significant advances can be seen in micro-electromechanical systems (MEMS). In such a network, it is desired to fulfill a pre-assigned task such as area coverage or target tracking by utilizing a distributed control strategy [33], [45]. Each agent sends its local information to a group of agents and receive same information from the other agents. The agent uses this information for generating the proper control command for itself.

A distributed control and coordination algorithm for groups of vehicles is presented in [45]. In this case, the authors proposed a gradient descent algorithm to find the centroid of each agents' Voronoi region. A similar approach is introduced in [46]. In this article, A distributed control strategy is developed to guide every mobile heterogeneous robot to the centroid of its Enhanced Multiplicatively Weighted Voronoi (EMWV) partition. The work of [47] presents a method to the deployment problem of mobile sensor networks in which agents have limited energy budgets to move and this leads to a novel partitioning structure. Indeed, it is desired to develop deployment strategies to relocate the sensors in such a way that the coverage of the network is increased, subject to some constraints such as communication capabilities and obstacle avoidance and it can be based on the features of a particular application. Moreover, no available information of the former position of the sensors might be existed [48], [49].

While aforementioned results are proved to be efficient in a wide-ranging of applications, they usually consider that the coverage priority of different parts of the field is uniform because of the similar importance of coverage of these parts in the network. Some deployment protocols is studied in a non-uniform area in [38], [26], [28] and [29].

There are two main challenges concerning a coverage problem of mobile sensor networks. The first one is increasing the coverage of the prioritized parts of the field, that needs the movements of mobile sensors toward those areas. The second challenge is the fact that covering the other parts of the network has a less importance; however, it is desirable to decrease the coverage holes in the network. In this case, a distributed algorithm can be used to lead the sensors in order to reach a such a trade off.

In this chapter, some self-deployment algorithms problem are investigated for a mobile sensor network in presence of failure. In the proposed solutions every sensor uses its local information received from the neighbors to compute the next potential position inside its corresponding Voronoi region. The main idea behind these algorithms is that the mobile sensors are going to displaced iteratively in a way that increases the coverage of the alert area and after that compensate the coverage holes in the network. Hence, with respect to the different objectives of these strategies, each sensor has two choices to utilize for finding the next candidate point in each iteration. The salient feature of the proposed solutions is that the coverage of the insecure area and also rest of the network is observed.

The remainder of the chapter is organized as follows. The problem and a few important notations is defined and formulated in Section 3.2. The main contribution of the chapter is subsequently presented where new algorithms are proposed in Section 3.3. In Section 3.4, the comparative simulations are demonstrated to show the effectiveness of the results, and finally in Section 3.5 some concluding remarks are provided.

3.2 Problem Formulation

Consider a sensor network consisting of n mobile sensors which are randomly distributed in a field. It is assumed that all sensors have the similar sensing strength and also the sensing radius of each one is a circle centered at the location of the sensor. Let $\phi(q)$ be a density function that represents the coverage importance of point q. Under the proposed strategy, this weight function is utilized for choosing the next position of each mobile sensor inside its corresponding Voronoi polygon.

Once sensors receive an emergency alert message from the neighbors, they are going to move toward the insecure area as long as the coverage of the alert area exceeds a certain percentage (ϵ). Afterwards, they are trying to compensate the coverage holes of the network located outside the alert zone. Infact, the goal is increasing the coverage inside the alert area and then decreasing the coverage holes outside the area.

In the rest of this chapter, $\mathcal{D}$ is referred to as the Voronoi diagram which is formed based on the sensing range and location of sensors.

Assumption 3.1. *It is assumed in this work that the communication graph of the mobile sensors in the network is connected. Consequently, each sensor can receive information of other sensors and localize itself in the plane.*

In the sequel, Definition 3.1 and Definition 3.2 are presented which point out the coverage of alert area by mobile sensors.

Definition 3.1. Consider a mobile sensor S_i, $i \in \mathbf{n}$, with the sensing radius r, and let the Voronoi polygon of the alert sensor right before the alert signal was generated be Π_f. The intersection of the region Π_f and the sensing disk of sensor S_i, which, by assumption, is a circle of radius r centered at P_i, and is denoted by $C(P_i, r)$, is called the *local coverage area* of the i-th sensor, and is denoted by β_i. Moreover, the intersection of the alert area and the union of the local coverage areas with the alert area is referred to as the *total coverage area*, and is denoted by β.

Definition 3.2. Part of the *local coverage area* of the i-th sensor which is only covered by sensor S_i is referred to as the *local exclusive coverage area* of the i-th sensor. Denote this area by λ_i, and the intersection of the alert area and the union of all local exclusive coverage area and the alert area by λ, i.e., $\lambda = \sum_{i=1}^{n} \lambda_i$. This intersection area will hereafter be referred to as the *total exclusive coverage area*.

Definition 3.3. Consider the mobile sensor S_i where $i \in n$ with the sensing radii R_s and Π_i denotes the Voronoi region of this sensor. The intersection of the polygon Π_i and the sensing disk centered at the location P_i of the sensor S_i is referred to as the *i-th conventional coverage area w.r.t.* P_i and is called the *local conventional coverage area* of the sensor. Consider this area be denoted by C_i.

Definition 3.4. The *centroid*(or the geometric center) of a polygon is the intersection point of all lines that divide the polygon into two parts of equal area. So, the point is the average of all points of the polygon. Assume a Voronoi polygon with N vertices labeled $(x_0, y_0), ..., (x_{N-1}, y_{N-1})$. The closed-form expression representing the centroid (C_x, C_y) is well known as follows [45]:

$$A = \frac{1}{2} \sum_{k=0}^{N-1} (x_k y_{k+1} - x_{k+1} y_k) \tag{3.1}$$

$$C_x = \frac{1}{6A} \sum_{k=0}^{N-1} (x_k + x_{k+1})(x_k y_{k+1} - x_{k+1} y_k) \tag{3.2}$$

$$C_y = \frac{1}{6A}\sum_{k=0}^{N-1}(y_k + y_{k+1})(x_k y_{k+1} - x_{k+1} y_k) \tag{3.3}$$

3.3 Deployment Protocol

In this section, some novel distributed protocols in a mobile sensor network are proposed to cover the alert area as well as the other parts of the network. At first, the alert sensor transmits local information to the neighbors and the neighbors propagate it to the others. Once a sensor be aware of a failure in the network, it initiates to assign a proper weight $\phi(q)$ to the points of its own Voronoi polygon with respect to its received information.

3.3.1 Method 1

For a point q, the weight is positive and its absolute value depends on the distance between q and the alert sensor. More precisely:

$$\phi(q) = \exp^{-\alpha(q_1 - x_f)^2 - \alpha(q_2 - y_f)^2} \tag{3.4}$$

where $P_f = [x_f, y_f]^T$ denotes the location of the alert sensor and α is a constant value.

At the begining, the mobile sensors are going to cover the insecure area by means of Algorithm 2 and The Maximum Weighted Vertex (MWV) Strategy as far as the coverage factor of aforementioned area exceeds a certain percentage (ϵ). Consequently, the network initiating to apply Algorithm 3 to every mobile sensor which is located outside the alert zone in order to compensate its local coverage hole in its Voronoi region. Besides, the other sensors keep covering the alert area by utilizing Algorithm 2 and MWV Strategy.

Algorithm 2 Increasing the Alert Area Coverage

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1) *Communication*: Every sensor transmits its location information to its neighbors and receives the same information from them.
2) *Voronoi Diagram*: Every sensor constructs its Voronoi polygon using the information received from its neighbors.
3) *Coverage calculation*: Every sensor obtains its local coverage and local exclusive coverage.
4) *Next location*: Each sensor computes its destination point in its Voronoi polygon based on the Maximum Weighted Vertex (MWV) deployment strategy [29].
5) *Movement conditions*: For any sensor with a nonzero local coverage, if the local coverage area and local exclusive coverage area both increase by a certain percentage by moving to the new position, it moves there; otherwise, it remains in its current location. For any other sensor, if by moving to the new position its distance with the alert area Π_f decreases by a certain percentage, it moves there; otherwise, it remains in its current position.
6) *Termination condition*: If at least one sensor moves to a new location, the algorithm repeats from step 1; otherwise, it is terminated.

Under The Maximum Weighted Vertex (MWV) Strategy, sensor S_i moves toward the vertex of the i-th region which has the maximum weight and it is denoted by $V_{i,m}$. In accordance with the strategy, when the alert message be received by a sensor, it finds the vertex with maximum weight in the corresponding polygon and if the aforementioned movement conditions be satisfied, the sensor moves toward that vertex and continues moving until that vertex is covered.

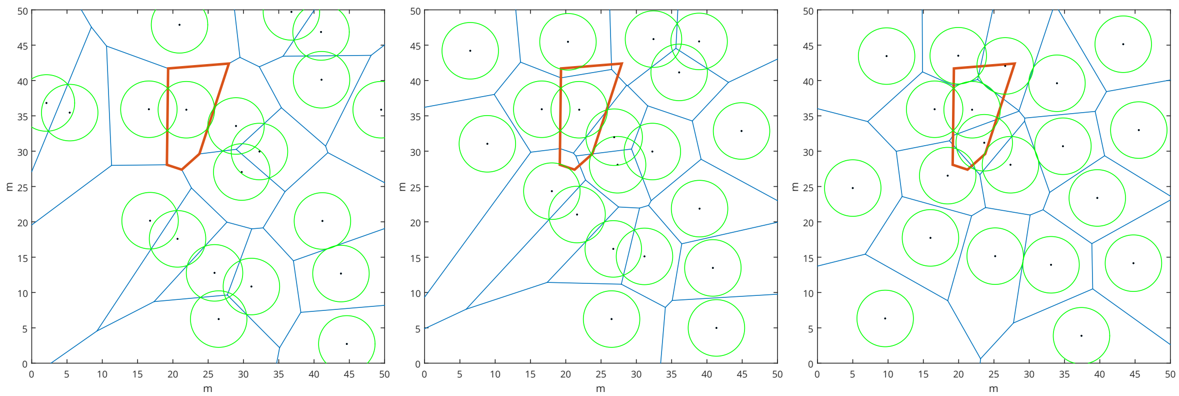
It is straightforward that the Algorithm 2 is similar to the algorithm that is used in

Algorithm 3 Increasing Coverage of network in Mobile Sensor Networks

1) Every sensor transmits information includes its location to the other sensors and receive same information from them.
2) Each sensor constructs its Voronoi region with the aid of information received from the neighbors.
3) Every sensor calculates its local conventional coverage.
4) Each mobile sensor computes its destination point which is the Centroid point of its Voronoi polygon.
5) If the local conventional coverage area would increase by a certain threshold, the sensor moves to the new position; otherwise, it remains in its current location.
6) If at least one sensor moves to a new location, the algorithm repeats from the first step; otherwise, the algorithm is terminated.

chapter 2. Thus, based on the proof of Theorem 2.1, the coverage of alert area increases in each round. Furthermore, by using an approach similar to the proof of Theorem 1 in [34], it can be implied that under the Algorithm 3, the local conventional coverage area in the remaining part of the network(those parts of the plane which are totally secure) increases.

Example 3.1. *To demonstrate the performance of method 1, this approach is simulated in a 50 m by 50 m square sensing field. In this example, 20 mobile sensors with a sensing radius of* 4m *are randomly deployed. Moreover,* α *and* ϵ *are set as 0.4 and 0.7. The initial and final positions of the sensors along with the corresponding Voronoi diagram and sensing circles are shown in Fig. 3.1. It can be seen from the figure that a few sensors move toward the alert area and other sensors relocate in such a way that minimize the coverage holes in the corresponding polygon.*



(a) (b) (c)

Figure 3.1: Configurations of the movements of sensors and the corresponding Voronoi-Diagram under the execution of method 1. 3.1(a) Initial coverage, 3.1(b) coverage after the first round, and 3.1(c) Final coverage

3.3.2 Method 2

For a point q in this method, the weight $\phi(q)$ equals to 1 if and only if this point is located inside the alert area; otherwise it equals to 0:

$$\phi(q) = \begin{cases} 1 & q \in \Pi_f \\ 0 & q \notin \Pi_f \end{cases} \tag{3.5}$$

where Π_f denotes the alert area.

After receiving the alert message, the mobile sensors move toward the insecure zone under Algorithm mentioned below and The Maximum Weighted Vertex (MWV) Strategy as long as the coverage of alert area meets the prespecified threshold. Then, we apply a same algorithm with a new strategy and a new weight function to the network in order to decrease the local coverage holes. The new Strategy is similar to The Farthest Weighted Vertex Strategy proposed in [30] which is called The Farthest Vertex Strategy (FV).

The new weight function can be defined as follows:

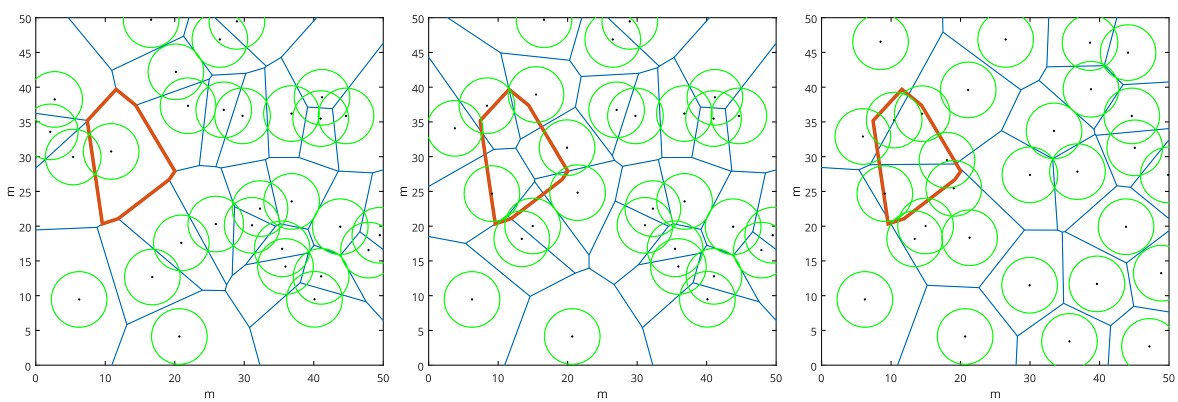
$$\phi(q) = \begin{cases} 0 & q \in \Pi_f \\ \\ 1 & q \notin \Pi_f \end{cases} \tag{3.6}$$

In this protocol, the proposed iterative algorithm in [29] is utilized for increasing coverage of alert zone. Each iteration in this algorithm includes four phases.

In the first phase, every sensor transmits its position and sensing radius to neighbors, and constructs its Voronoi polygon subsequently based on the information it receives from others. Then, in the second phase, each sensor uses the available information to compute its destination point in its Voronoi region based on the deployment strategy. When the new target location is specified, the weighted coverage area w.r.t. this location is obtained in the third phase. If this value is greater than the previous local weighted coverage area, then the sensor moves to the new destination; otherwise, it remains in its current location. Finally, in the last phase, if the local weighted coverage area by none of the sensors is increased by a certain percentage, then the iteration terminates.

Under The Farthest Vertex (FV) Strategy, sensor S_i moves toward the vertex of the i-th region which has the maximum distance to itself and it is denoted by $V_{i,fv}$. With regard to this strategy, when the alert message be received by a sensor, it finds the vertex with maximum distance in the corresponding polygon and if the aforementioned movement conditions be satisfied, the sensor moves toward that vertex and continues moving until that vertex is covered.

Example 3.2. *To illustrate the coverage performance of method 2, assume that 30 identical sensors with* $r = 4m$ *are deployed in a 50 m by 50 m square sensing field. Using this proposed technique with* $\epsilon = 0.7$ *for the coverage threshold of alert area, the configuration of the sensors depicted in Fig. 3.2. It is straightforward from the figure that after meeting the coverage threshold by some sensors (red circles), other sensors (green circles) are trying to compensate the coverage lost outside the alert area.*



(a) (b) (c)

Figure 3.2: Configurations of the movements of sensors and the corresponding Voronoi-Diagram under the execution of method 2. 3.2(a) Initial coverage, 3.2(b) coverage after the first round, and 3.2(c) Final coverage

3.3.3 Method 3

For a point q in this method, the weight $\phi(q)$ equals to K_2 if and only if this point is located inside the alert area; otherwise it equals to K_1:

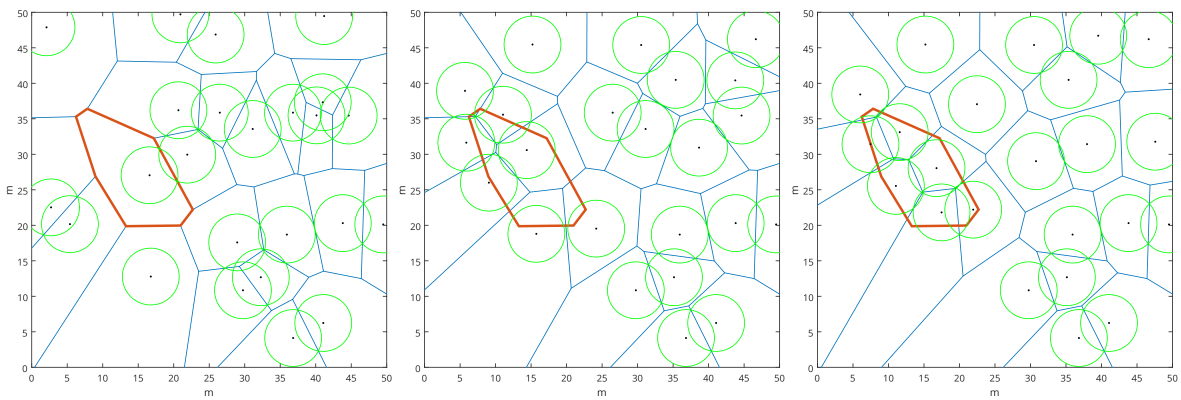
$$\phi(q) = \begin{cases} K_2 & q \in \Pi_f \\ \\ K_1 & q \notin \Pi_f \end{cases} \tag{3.7}$$

where Π_f denotes the alert area and K_2, K_1 are positive constants ($K_2 > K_1$). Indeed, the priority of covering the points within the alert zone are greater than others.

Once the alert message transmits to the all mobile sensors, an algorithm same as the algorithm used in 3.3.2 and The Maximum Distance Weighted Vertex (MDWV) Strategy (which is similar to the strategy used in [29]) is applied to the network.

Under The Maximum Distance Weighted Vertex (MDWV) Strategy, sensor S_i moves toward the vertex of the i-th region whose distance from itself multiplied by its weight is maximum and it is denoted by $V_{i,mdwv}$. With respect to this strategy, when the alert message be received by a sensor, it finds the vertex with maximum multiplication of distance from itself and weight in the corresponding polygon and if the aforementioned movement conditions be satisfied, the sensor moves toward that vertex and continues moving until that vertex is covered.

Example 3.3. *Let method 3 be applied to a network of 24 identical mobile sensors in* *a 50 m by 50 m square sensing field and* $r = 4m$*. The snapshots of mobile sensors positions are shown in Fig. 3.3. The results confirm that mobile sensors move toward the area with higher coverage importance which causes the coverage increment in both of the alert area and rest of the network.*



(a) (b) (c)

Figure 3.3: Configurations of the movements of sensors and the corresponding Voronoi-Diagram under the execution of method 3. 3.3(a) Initial coverage, 3.3(b) coverage after the first round, and 3.3(c) Final coverage

3.4 Comparative Results

Example 3.4. *In order to verify the validity of the proposed algorithms, a few simulations are considered in this example to compare their performance with each other. To eliminate the error caused by randomness, every simulation was run for 20 times and the average of results is shown. The values of parameters are set as* $\alpha = 0.4$, $\epsilon = 0.7$ *and* $r = 2.5m$*. Also, all the simulations utilize randomly distributed different number of*

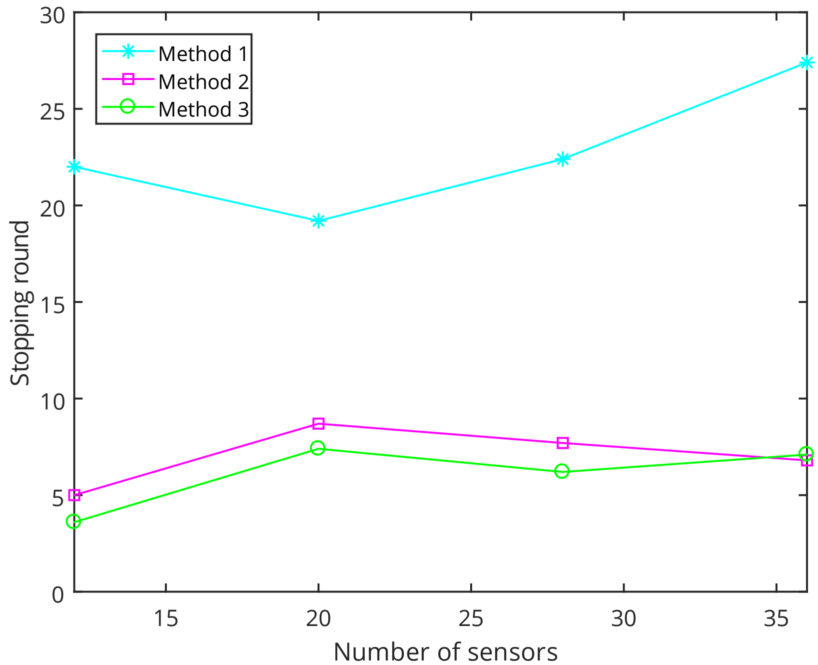


Figure 3.4: The number of required iteration to reach the termination conditions for different number of sensors using the proposed techniques.

sensors ($n = 12, 20, 28, 36$) *within a* $40m \times 40m$ *sensing field.*

This simulation evaluates the performance of the introduced methods in terms of stopping round. The number of iterations versus the number of mobile sensors is given in Fig. 3.4. As it can be seen from this figure, second and third method result in a less required iteration for convergence compared to the first method. Moreover, these superior methods have a same result for different number of sensors and there is not much round increment by increasing the number of sensors.

Another important aspect of evaluating efficiency of sensor deployment methods is

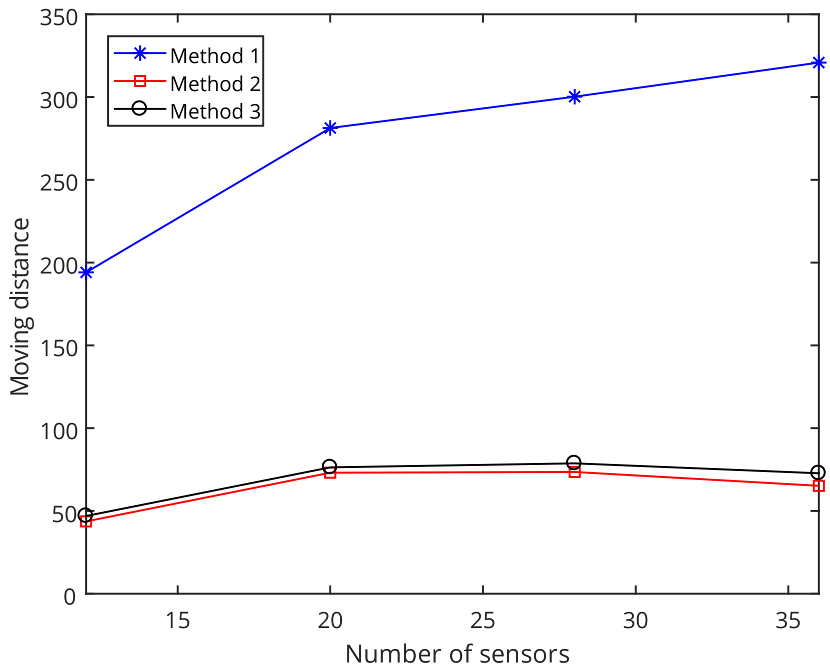


Figure 3.5: Average moving distance for different number of sensors, using the proposed algorithms.

the energy consumption of the sensors. The most substantial elements of energy consumption are traveling distance by the mobile sensors as well as the number of stopping times before arriving at the desired position. Fig. 3.5 shows the average traveling distance of mobile sensors for different number of sensors. As we can observe from the figure, method 2 and method 3 outperform the other method and this superiority is significant. Also, by increasing the number of deployed sensors, the traveling distance under the mentioned algorithms does not change a lot.

The total number of sensor movements versus the number of sensors is illustrated in Fig. 3.6. It clearly shows that the total number of sensor displacements for different

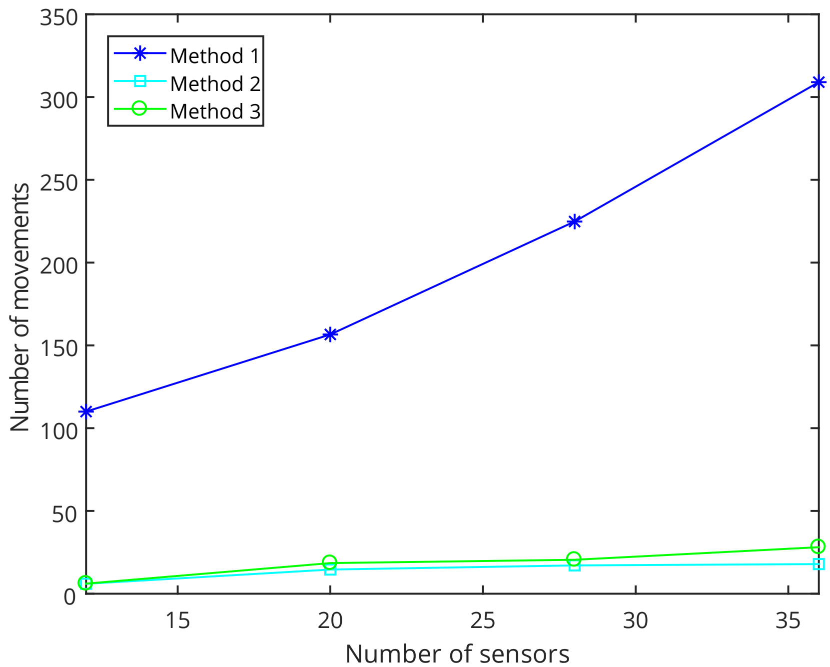


Figure 3.6: Number of sensor displacements for different number of sensors, using the proposed deployment methods.

number of sensors under the second and third method is smaller than that in the another method considerably. This is due to the fact that by applying the first method a large number of sensors will move toward the insecure area. On the other hand, under the second and third methods a few number of mobile sensors are going to relocate within the field to detect the alert zone. As a result, it causes less displacements and then less traveling distances. So it can be concluded that method 2 and method 3 are better candidates for field coverage in presence of failure as long as energy consumption is considered.

In Fig. 3.7 the overall coverage of network is depicted for different number of mobile

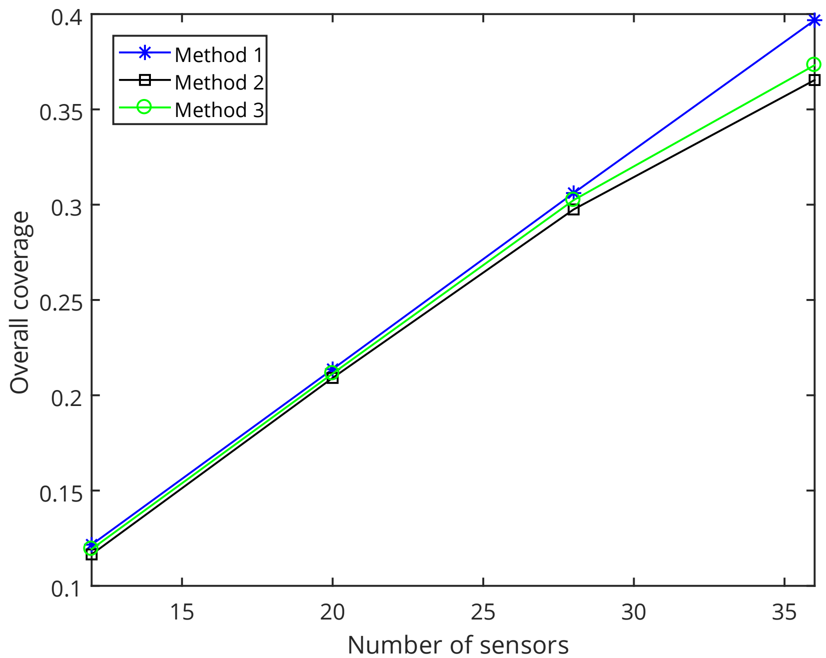


Figure 3.7: Overall network coverage for different number of sensors using the proposed algorithms.

sensors. It can be seen from the figure, when there are a small number of sensors in the network, the overall coverage of all methods are approximately the same. However, when there are a large number of sensors are deployed in the field, the first method outperforms the others.

3.5 Conclusions

In this chapter, some distributed deployment algorithms are proposed for a network of mobile sensors where the network is subject to an alert situation. The goals of these protocols are covering the insecure area and then decreasing the coverage holes inside the field. A notion of Voronoi diagram is used. By using this kind of diagram, the plane is partitioned among all sensors based on their received information and a displacement coordination algorithm is applied to sensors to guide some of them toward the insecure area. Afterward, other sensors are going to move in such a way that compensates the local coverge holes inside the network. Simulation results demonstrate the efficacy of the proposed methods.

Chapter 4

Conclusions and Future Directions

The problem of coverage maximization in a mobile sensor network (MSN) in the presence of failure is studied in this thesis. It was assumed that the sensors distribute randomly in the field. Voronoi diagram is used for partitioning the network to some regions and each area is assigned to a mobile sensor for controlling its coverage. The alert message sends from the alert sensor to its neighbors and they will send it to their own neighbors. Once all the sensors be aware of the alert condition and its location, the proposed algorithms apply to the network to increase the coverage of alert zone and detect the unknown problem.

Efficient sensor deployment algorithms are presented in chapter 2 for detecting the failure inside the alert area. In this context, some techniques are proposed to maximize the coverage factor of above mentioned area by mobile sensors displacement. Based on these methods, each sensor moves iteratively in a direction that the coverage area in the alert zone increases or the distance to this area decreases. In these methods, we used the concept of conventional coverage area, exclusive coverage area and weighted coverage area. The comparative results show that the first method is outperformed from the view point of coverage and the second method is more efficient in consuming energy.

Three distributed deployment techniques are proposed in chapter 3 to minimize the coverage lost in all parts of the field after monitoring the insecure zone. First of all, a certain percentage is determined as a threshold for alert area coverage. When the coverage threshold is met, we apply some algorithms to the non-intersected sensors with the alert zone. Using these algorithms, the sensors move iteratively to decrease coverage holes in the sensing plane. In these methods, we used the concept of conventional coverage area and weighted coverage area. Simulation results are provided to confirm the efficacy of the introduced methods in increasing the network coverage.

4.1 Future Research Directions

Some suggestions and possible extensions for future study in this area are outlined below:

- Extending the problem of failure detecting to the non-uniform and probabilistic sensing patterns where the likelihood of coverage are supposed to be maximized.

- Considering the case of non-connected communication graph and link failure in maximizing the coverage.

- As an extension, it would be possible to study the problem of alert area coverage improvement in presence of obstacles in the field.

- One can develop a variation of these algorithms by adding power and lifetime constraint to this coverage problem which would be more practical.

- Modifying the field to two separate areas (alert area and rest of the plane) and applying proposed strategies to these areas simultaneously. Indeed, the network is partitioned to two separate areas that each one constructs its own Voronoi diagram.

Bibliography

[1] L. Muduli, D. P. Mishra, and P. K. Jana, "Application of wireless sensor network for environmental monitoring in underground coal mines: A systematic review," *Journal of Network and Computer Applications*, vol. 106, pp. 48–67, 2018.

[2] B. Rashid and M. H. Rehmani, "Applications of wireless sensor networks for urban areas: A survey," *Journal of Network and Computer Applications*, vol. 60, pp. 192–219, 2016.

[3] M. Delamo, S. Felici-Castell, J. J. Pérez-Solano, and A. Foster, "Designing an open source maintenance-free environmental monitoring application for wireless sensor networks," *Journal of Systems and Software*, vol. 103, pp. 238–247, 2015.

[4] D. He, N. Kumar, J. Chen, C.-C. Lee, N. Chilamkurti, and S.-S. Yeo, "Robust anonymous authentication protocol for health-care applications using wireless medical sensor networks," *Multimedia Systems*, vol. 21, no. 1, pp. 49–60, 2015.

[5] S. Vasuhi and V. Vaidehi, "Target tracking using interactive multiple model for wireless sensor network," *Information Fusion*, vol. 27, pp. 41–53, 2016.

[6] Y. Qu and S. V. Georgakopoulos, "Relocation of wireless sensor network nodes using a genetic algorithm," in *Proceedings of the IEEE WAMICON Conference*, 2011, pp. 1–5.

[7] R. W. R. de Souza, L. R. Moreira, J. J. Rodrigues, R. R. Moreira, and V. H. C. de Albuquerque, "Deploying wireless sensor networks–based smart grid for smart meters monitoring and control," *International Journal of Communication Systems*, vol. 31, no. 10, p. e3557, 2018.

[8] F. Castaño, E. Bourreau, N. Velasco, A. Rossi, and M. Sevaux, "Exact approaches for lifetime maximization in connectivity constrained wireless multi-role sensor networks," *European Journal of Operational Research*, vol. 241, no. 1, pp. 28–38, 2015.

[9] A. Jain, "Betweenness centrality based connectivity aware routing algorithm for prolonging network lifetime in wireless sensor networks," *Wireless Networks*, vol. 22, no. 5, pp. 1605–1624, 2016.

[10] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. H. Hanzo, "A survey of network lifetime maximization techniques in wireless sensor networks," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 2, pp. 828–854, 2017.

[11] H. Yetgin, K. T. K. Cheung, M. El-Hajjar, and L. Hanzo, "Network-lifetime maximization of wireless sensor networks," *IEEE Access*, vol. 3, pp. 2191–2226, 2015.

[12] H. Mahboubi, A. G. Aghdam, and K. Sayrafian-Pour, "Toward autonomous mobile sensor networks technology," *IEEE Transactions on Industrial Informatics*, vol. 12, no. 2, pp. 576–586, 2016.

[13] M. Rout and R. Roy, "Dynamic deployment of randomly deployed mobile sensor nodes in the presence of obstacles," *Ad Hoc Networks*, vol. 46, pp. 12–22, 2016.

[14] M. Vecchio and R. López-Valcarce, "Improving area coverage of wireless sensor networks via controllable mobile nodes: A greedy approach," *Journal of Network and Computer Applications*, vol. 48, pp. 1–13, 2015.

[15] A. K. Idrees, K. Deschinkel, M. Salomon, and R. Couturier, "Distributed lifetime coverage optimization protocol in wireless sensor networks," *The Journal of Supercomputing*, vol. 71, no. 12, pp. 4578–4593, 2015.

[16] J. Yu, S. Wan, X. Cheng, and D. Yu, "Coverage contribution area based k-coverage for wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 9, pp. 8510–8523, 2017.

[17] M. Ma and Y. Yang, "Adaptive triangular deployment algorithm for unattended mobile sensor networks," *IEEE Transactions on Computers*, vol. 56, no. 7, pp. 946–847, 2007.

[18] Y.-C. Wang, C.-C. Hu, and Y.-C. Tseng, "Efficient placement and dispatch of sensors in a wireless sensor network," *IEEE Transactions on Mobile Computing*, vol. 7, no. 2, pp. 262–274, 2007.

[19] C.-Y. Chang, C.-T. Chang, Y.-C. Chen, and H.-R. Chang, "Obstacle-resistant deployment algorithms for wireless sensor networks," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 6, pp. 2925–2941, 2008.

[20] Z. Shen, Y. Chang, H. Jiang, Y. Wang, and Z. Yan, "A generic framework for optimal mobile sensor redeployment," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 8, pp. 4043–4057, 2010.

[21] S. Yangy, M. Liz, and J. Wu, "Scan-based movement-assisted sensor deployment methods in wireless sensor networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 18, no. 8, pp. 1108–1121, 2007.

[22] Z. Jing and Z. Jian-Chao, "A virtual centripetal force-based coverage-enhancing algorithm for wireless multimedia sensor networks," *IEEE Sensors Journal*, vol. 10, no. 8, pp. 1328–1334, 2010.

[23] G. Wang, G. Cao, and T. F. La Porta, "Movement-assisted sensor deployment," *IEEE Transactions on Mobile Computing*, vol. 5, no. 6, pp. 640–652, 2006.

[24] Y. Qu, "Wireless sensor network deployment," Ph.D. dissertation, Florida International University, 2013.

[25] J. Jia, J. Chen, G. Chang, Y. Wen, and J. Song, "Multi-objective optimization for coverage control in wireless sensor network with adjustable sensing radius," *Computers & Mathematics with Applications*, vol. 57, no. 11-12, pp. 1767–1775, 2009.

[26] J. Cortes, S. Martinez, and F. Bullo, "Spatially-distributed coverage optimization and control with limited-range interactions," *ESAIM: Control, Optimisation and Calculus of Variations*, vol. 11, no. 4, pp. 691–719, 2005.

[27] F. Bullo, J. Cortes, and S. Martinez, *Distributed control of robotic networks: a mathematical approach to motion coordination algorithms.* Princeton University Press, 2009, vol. 27.

[28] J. Cortés, "Coverage optimization and spatial load balancing by robotic sensor networks," *IEEE Transactions on Automatic Control*, vol. 55, no. 3, pp. 749–754, 2010.

[29] H. Mahboubi, J. Habibi, A. G. Aghdam, and K. Sayrafian-Pour, "Distributed deployment strategies for improved coverage in a network of mobile sensors with prioritized sensing field," *IEEE Transactions on Industrial Informatics*, vol. 9, no. 1, pp. 451–461, 2013.

[30] ——, "Distributed coverage optimization in a network of static and mobile sensors," in *Proceedings of the 2013 American Control Conference*, 2013, pp. 6877–6881.

[31] M. Moh, B. J. Culpepper, L. Dung, T.-S. Moh, T. Hamada, and C.-F. Su, "On data gathering protocols for in-body biomedical sensor networks," in *Proceedings of the IEEE Global Telecommunications Conference*, vol. 5, 2005, pp. 6–pp.

[32] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," *Computer Networks*, vol. 38, no. 4, pp. 393–422, 2002.

[33] H. Mahboubi, A. Momeni, A. G. Aghdam, K. Sayrafian-Pour, and V. Marbukh, "An efficient target monitoring scheme with controlled node mobility for sensor networks," *IEEE Transactions on Control Systems Technology*, vol. 20, no. 6, pp. 1522–1532, 2012.

[34] H. Mahboubi, K. Moezzi, A. G. Aghdam, and K. Sayrafian-Pour, "Distributed deployment algorithms for efficient coverage in a network of mobile sensors with non-identical sensing capabilities," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 8, pp. 3998–4016, 2014.

[35] A. Boukerche and X. Fei, "A voronoi approach for coverage protocols in wireless sensor networks," in *Proceedings of the IEEE Global Telecommunications Conference*, 2007, pp. 5190–5194.

[36] A. Konstantinidis, K. Yang, and Q. Zhang, "An evolutionary algorithm to a multi-objective deployment and power assignment problem in wireless sensor networks," in *Proceedings of the IEEE Global Telecommunications Conference*, 2008, pp. 1–6.

[37] S. Susca, F. Bullo, and S. Martinez, "Monitoring environmental boundaries with a robotic sensor network," *IEEE Transactions on Control Systems Technology*, vol. 16, no. 2, pp. 288–296, 2008.

[38] J. Habibi, H. Mahboubi, and A. G. Aghdam, "A gradient-based coverage optimization strategy for mobile sensor networks," *IEEE Transactions on Control of Network Systems*, vol. 4, no. 3, pp. 477–488, 2017.

[39] S. Loriot and F. Cazals, "Modeling macro–molecular interfaces with intervor," *Bioinformatics*, vol. 26, no. 7, pp. 964–965, 2010.

[40] J. Jiang, S. Wen, S. Yu, Y. Xiang, and W. Zhou, "K-center: An approach on the multi-source identification of information diffusion," *IEEE Transactions on Information Forensics and Security*, vol. 10, no. 12, pp. 2616–2626, 2015.

[41] L. Zhou and P. Tokekar, "Active target tracking with self-triggered communications in multi-robot teams," *IEEE Transactions on Automation Science and Engineering*, no. 99, pp. 1–12, 2018.

[42] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed diffusion: A scalable and robust communication paradigm for sensor networks," in *Proceedings of the 6th Annual International Conference on Mobile Computing and Networking*, 2000, pp. 56–67.

[43] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Communications of the ACM*, vol. 43, no. 5, pp. 51–58, 2000.

[44] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie, "Protocols for self-organization of a wireless sensor network," *IEEE Personal Communications*, vol. 7, no. 5, pp. 16–27, 2000.

[45] J. Cortes, S. Martinez, T. Karatas, and F. Bullo, "Coverage control for mobile sensing networks," *IEEE Transactions on Robotics and Automation*, vol. 20, no. 2, pp. 243–255, 2004.

[46] P.-X. Wu, J.-M. Li, and T.-H. Cheng, "Distributed coverage control with dependent density functions," in *Proceedings of the 57th IEEE Conference on Decision and Control*, 2018, pp. 1299–1304.

[47] A. Kwok and S. Martinez, "Deployment algorithms for a power-constrained mobile sensor network," *International Journal of Robust and Nonlinear Control*, vol. 20, no. 7, pp. 745–763, 2010.

[48] D. Wang, J. Liu, and Q. Zhang, "Mobility-assisted sensor networking for field coverage," in *Proceedings of the IEEE Global Telecommunications Conference*, 2007, pp. 1190–1194.

[49] H. Mahboubi, F. Sharifi, A. G. Aghdam, and Y. Zhang, "Distributed coordination of a network of nonidentical agents with limited communication capabilities in the

presence of fixed obstacles," in *Proceedings of the American Control Conference*, 2013, pp. 5398–5403.