A GIS Based Wireless Sensor Network Coverage Estimation and Optimization: A Voronoi Approach

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Abstract. Recent advances in sensor technology have resulted in the design and development of more efficient and low cast sensor networks for environmental monitoring, object surveillance, tracking and controlling of moving objects, etc. The deployment of a sensor network in a real environment presents several challenging issues that are often oversimplified in the existing solutions. Different approaches have been proposed in the literatures to solve this problem. Many of these approaches use Voronoi diagram and Delaunay triangulation to identify sensing holes in the network and create an optimal arrangement of the sensors to eliminate the holes. However, most of these methods do not consider the reality of the environment in which the sensor network is deployed. This paper presents a survey of the existing solutions for geosensor network optimization that use Voronoi diagram and Delaunay triangulation and identifies their limitations in a real world application. Next, it proposes a more realistic approach by integrating spatial information in the optimization process based on Voronoi diagram. Finally the results of two cases studies based on the proposed approach in natural area and urban environment are presented and discussed.

Keywords: geosensor networks deployment, coverage problem, Voronoi diagram, Delaunay triangulation, GIS.

1 Introduction

Recent advances in electomechanical and communication technologies have resulted in the development of more efficient, low cost and multi-function sensors. These tiny and ingenious devices are usually deployed in a wireless network to monitor and collect physical and environmental information such as motion, temperature, humidity, pollutants, traffic flow, etc [7]. The information is then communicated to a process center where they are integrated and analyzed for different application. Deploying sensor networks allows inaccessible areas to be covered by minimizing the

M.L. Gavrilova et al. (Eds.): Trans. on Comput. Sci. XIV, LNCS 6970, pp. 151–172, 2011.

sensing costs compared to the use of separate sensors to completely cover the same area. Sensors may be spread with various densities depending on the area of application and the details and the quality of the information required.

Despite the advances in the sensor network technology, the efficiency of a sensor network for collection and communication of the information may be constrained by the limitations of sensors deployed in the network nodes. These restrictions may include sensing range, battery power, connection ability, memory, and limited computation capabilities. These limitations have been addressed by many researchers in recent years from various disciplines in order to design and deploy more efficient sensor networks [28].

Efficient sensor network deployment is one of the most important issues in sensor network filed that affects the coverage and communication between sensors in the network. Nodes use their sensing modules to detect events occurring in the region of interest. Each sensor is assumed to have a sensing range, which may be constrained by the phenomenon being sensed and the environment conditions. Hence, obstacles and environmental conditions affect network coverage and may result in holes in the sensing area. Communication between nodes is also important. Information collected from the region should be transferred to a processing center, directly or via its adjacent sensor. In the later case, each sensor needs to be aware of the position of other adjacent sensors in their proximity.

Several approaches have been proposed to detect and eliminate holes and hence increase sensor networks coverage through optimization methods [9, 23, 24, 26, 39, 40, 41]. Many of these approaches use Voronoi diagram and Delaunay triangulation to identify sensing holes in the network and create an optimal arrangement of the sensors to eliminate the holes. However, most of these methods over simplify the environment in which the sensor networks are deployed reducing the quality of spatial coverage estimation and optimization. This paper makes a critical overview of the existing solutions based on Voronoi diagrams and Delaunay triangulation for geosensor network coverage estimation and optimization. Next, it proposes a novel sensor network deployment approach by integrating spatial information in the optimization process based on Voronoi diagram.

The remainder of this paper is as follows. Section 2 presents a state of the art on the geosensor networks and their related issues. Section 3, describes the coverage problem in geosensor networks and different solutions found in the literature for its estimation and optimization. Section 4 presents the coverage determination and optimization solutions based on Voronoi and Delaunay triangulation and their limitations. Section 5 proposes a novel sensor network deployment approach by integrating spatial information in the optimization process based on Voronoi diagram. In section 6, we present the results of the two experimentations based on the proposed approach both in natural and urban areas. Finally, section 7 concludes the paper and proposes new avenues for the future works.

2 State of the Art on Geosensor Networks and Their Applications

Sensor networks were announced as one of the most important technologies for the 21st century in 1999 by *Business Week* [46]. These networks are usually composed of a set of small, smart and low-cost sensors with limited on-board processing capabilities, storage and short-range wireless communication links based on radio technology. Previously, sensor networks consisted of small number of sensor nodes that were usually wired to a central processing station. However, nowadays, the focus is more on wireless, distributed, sensing nodes [6, 35, 42]. A sensor node is characterized by its sensing field, memory and battery power as well as its computation and communication capabilities. A sensor can only cover a small area. However, collaboration of a group of sensors with each other can cover a more significant sensing field and hence accomplishing much larger tasks. Each element of a group of sensors can sense and collect data from the environment, apply local processing, communicate it to other sensors and perform aggregations on the observed information [31].

Sensor networks are also referred to as *Geo*sensor networks as they are intensively used to acquire spatial information [28]. Hereafter, we will use both of the terms "sensors" and "geosensors" interchangeably. Geosensors can be deployed on the ground, in the air, under water, on bodies, in vehicles, and inside buildings.

Sensor networks have several applications including environmental monitoring, change detection, traffic monitoring, border security, and public security, etc. They are used for collecting the information needed by smart environments quickly and easily, whether in buildings, utilities, industries, home, shipboard, transportation systems automation, or elsewhere. Sensor networks are useful in vehicle traffic monitoring and control. Most traffic intersections have either overhead or buried sensors to detect vehicles and control traffic lights. Furthermore, video cameras are frequently used to monitor road segments with heavy traffic, with the video sent to human operators at central locations [7]. Sensor networks can be used for infrastructure security in critical buildings and facilities, such as power plants and communication centers. Networks of video, acoustic, and other sensors provide early detection of possible threats [34]. Commercial industries has long been interested in sensing as a means of lowering cost and improving machine (and perhaps user) performance and maintainability. Monitoring machine "health" through determination of vibration or wear and lubrication levels, and the insertion of sensors into regions inaccessible by humans, are just two examples of industrial applications of sensors [7]. A broad classification of geosensor network applications is monitoring continuous phenomena (e.g., to assess plant health and growth circumstances, or to observe and measure geophysical processes), detecting real time events (e.g., flood and volcano), and tracking objects (e.g., animal monitoring) [28, 35, 42].

Sensor networks have some limitations when it comes to the modeling, monitoring and detecting environmental processes. Monitoring and analyzing dynamic objects in real time are also difficult. Examples of such processes include the observations of dynamic phenomena, (e.g., air pollution) or monitoring of mobile objects (e.g., animals in a habitat). It is necessary to know how to use this technology to detect and monitor those phenomena appropriately and efficiently. For this purpose, one needs to identify the relevant mix of hardware platforms for the phenomena type, the accessibility or inaccessibility of the observation area, hazardous environmental conditions, and power availability, etc. Today wireless sensor network technology are more effectively used for detecting and monitoring time-limited events (e.g., earthquake tremors), instead of continuous sampling in remote areas due to the battery constraints of geosensor platforms. [28].

3 Coverage Problem in Geosensor Networks

An important issue to deploy a sensor network is finding the best sensor location to cover the region of interest. Definition of coverage differs from an application to another. The so-called art gallery problem, for example, aims to determine the minimum number of required observers (cameras) to cover an art gallery room such that every point is seen by at least one observer [5]. Hence, here, the coverage is defined based on a direct visibility between the observer and the target point. In sensor networks, however, the coverage of a point means that the point is located in the sensing range of a sensor node, which is usually assumed to be uniform in all directions. In this case, the sensing range is represented by a disk around the sensor [3]. Failing this condition for some points in the region of interest will result in coverage holes (Fig. 1).

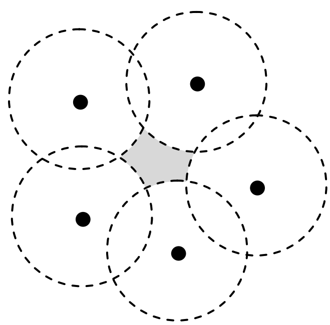


Fig. 1. Coverage hole (shaded region) in a sensor network with disk model sensing range

Regarding this definition of coverage in sensor network, the coverage problem basically means placing minimum number of nodes in an environment, such that every point in the sensing field is optimally covered [1, 11]. Nodes can either be placed manually at predetermined locations or dropped randomly in the environment. It is difficult to find a random scattering solution that satisfies all the coverage and connectivity conditions. Thus, the term of area coverage plays an important role in sensor networks and their connectivity.

The existing solutions to determine and optimize the coverage in sensor networks can be classified in two main categories of "exposure based" and "mobility based" approaches [11]. Exposure based solutions evaluate unauthorized intrusions in the networks. Mobility based solutions, however, exploit moving properties of nodes to get better coverage conditions and try to relocate sensor nodes to optimal locations that serve maximum coverage.

3.1 Coverage Based on Exposure

The estimation of coverage can be defined as a measure of the ability to detect objects within a sensor filed. The notion of *exposure* can represent such a measurement. It is described as the expected average ability of observing a target moving in a sensor field. It is related to coverage in the sense that "it is an integral measure of how well the sensor network can observe an object [exists in the field or] moving on an arbitrary path, over a period of time" [25].

A very simple, but nontrivial example of exposure problem is illustrated in Fig. 2. An object moves from point ***A*** to point ***B*** and there is only one sensor node ***S*** in the field. Obviously, the path 2 has the maximum exposure, because it is the shortest path from ***A*** to ***B*** and it passes through the sensor node ***S***. Thus, the object moves along this path is certainly tracked by ***S***. However, finding the path with the minimum exposure is tricky: although path 1 is the farthest path from the sensor node ***S*** and so intuitively seems to have the lowest exposure, it is also the longest path. Therefore, travelling along this path takes longer time and the sensor has longer time to track the moving object. It is shown that the minimum exposure path is 3, which is a trade-off between distance from the sensor and travelling time [18].

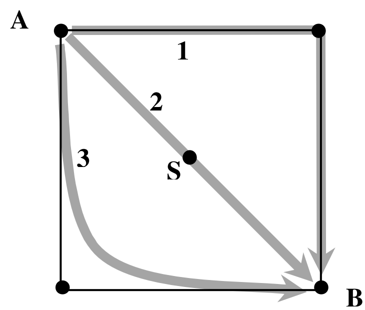


Fig. 2. Minimum and maximum exposure paths in a simple sensor network [18]

The so-called *worst* case and *best* case coverage are examples of methods for exposure evaluation [23, 26]. Worst-case coverage is the regions of lower observability from sensor nodes, so objects move along this path has the minimum probability to be detected. Best-case coverage, however, is the regions of higher observability from sensors, thus probability of detecting an object moving along this path is maximum [11]. These two parameters together give an insight of the coverage quality of the network and can help to decide if additional sensors must be deployed. Different approaches have been proposed in the literatures for the worst- and best-case coverage problems [19, 25, 27, 30, 37]. A Voronoi based solution for this problem is presented in section 4.

3.2 Coverage Based on Mobility

In some sensor placements approaches, where there is no information available about terrain surface and its morphology, random sensor placement is used. This method does not guarantee the optimized coverage of the sensing region. Thus, some deployment strategies take advantage of mobility options and try to relocate sensors from their initial places to optimize the network coverage. Potential field-based, virtual force-based and incremental self-deployment methods [14, 15, 44] are examples of such approach and are introduced, here. Other methods such as VEC, VOR and MiniMax, which are mobility based methods that use Voronoi diagram in their approach, are explained in the next section.

The idea of potential field is that every node is exposed to two forces: (i) a repulsive force that causes the nodes to repel each other, and (ii) the attractive force that makes nodes moving toward each other when they are on the verge of being disconnected [11, 15]. These forces have inverse proportion with the square of distance between nodes. Each node repels all its neighbors. This action decreased the repulsive force, but at the same time, it stimulates the attractive force. Eventually, it ends up in an arrangement in which all the nodes reach an equilibrium situation and uniformly cover the sensing field.

Virtual force-based method is very similar to potential-based, but here each node is exposed to three types of forces: (i) a repulsive force exerted by obstacles, (ii) an attractive force exerted by areas where the high degree of coverage is required, and (iii) attractive or repulsive force by another point based on its location and orientation [44, 45].

In incremental self-deployment algorithm each node finds its optimal location through previous deployed nodes information in four steps [12, 13, 14]: (i) *initialization* that classifies the nodes to three groups: waiting, active and deployed; (ii) *goal selection* that selects the best destination for the node to be deployed based on previous node deployment; (iii) *goal resolution* that assigns this new location to a waiting node and the plan for moving to this location is specified; (iv) Finally, *execution* that deploys the active nodes in their place.

As it is realized in the above algorithms, spatial coverage of sensor networks is much related to the spatial distribution of the sensors in the environment. In other words, the described algorithms try to distribute the sensors in the field so that the much possible coverage is obtained. Voronoi diagram and Delaunay triangulation are the data structures that directly satisfy the required distribution. They have been used for developing algorithms for both exposure and mobility based approaches.

4 Role of Voronoi Diagram and Delaunay Triangulation

This section presents the solutions for sensor network coverage optimisation that use Voronoi diagram and Delaunay triangulation for coverage determination and optimization in sensor networks. The solutions are categorized as coverage hole detection, healing the holes, and node scheduling. Some other challenges are introduced at the end of this section.

4.1 Coverage Hole Detection

In a simple sensor network – where the sensing regions of all sensors are identical circles – if a point is not covered by its closest sensor node, obviously it is not covered by any other sensor node. This property is the basis to use Voronoi diagram in sensor coverage problem: in a Voronoi diagram, all the points within a Voronoi cell are closest to the generating node that lies within this cell. Thus, having constructed the Voronoi diagram of the sensor nodes and overlaid the sensing regions on it (Fig. 3), if a point of a Voronoi cell is not covered by its generating node, this point is not covered by any other sensors [3, 9, 38, 39]. Although computing the area of a Voronoi cell is straightforward, computing the area of the uncovered region in a Voronoi cell is a complicated task, because the sensing regions may protrude the Voronoi cells and overlay each other. Strategies for this computation can be found in [9, 39].

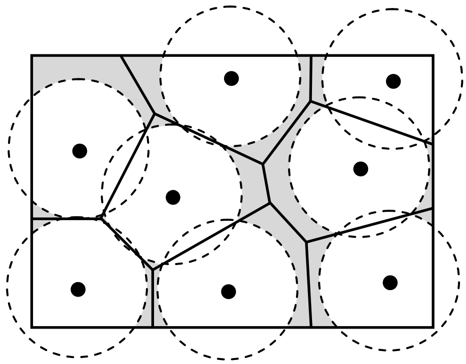


Fig. 3. Using Voronoi diagram to detect the coverage holes (shaded regions) in a sensor network

Another Voronoi-based approach to evaluate the coverage of a sensor network is based on the notion of *exposure*, which was discussed earlier in section III. To solve the worst-case coverage problem, a very similar concept, i.e., *maximal breach path* is used. It is the path through a sensing field between two points such that the distance from any point on the path to the closest sensor is maximized. Since the line segments of the Voronoi diagram has the maximum distance from the closest sites, the maximal breach path must lie on the line segments of the Voronoi diagram corresponding to the sensor nodes (Fig. 4). The Voronoi diagram of the sensor nodes is first constructed. This diagram is then considered as a weighted graph, where the weight of each edge is the minimum distance from the closest sensor. Finally, an algorithm uses breadth first and binary searches to find the maximal breach path [23, 26].

The best-case coverage problem is solved through the similar concept of *maximal support path*. This is the path through a sensing field between two points for which the distance from any point on it to the closest sensor is minimized. Intuitively, this is traveling along straight lines connecting sensor nodes. Since the Delaunay triangulation produces triangles that have minimal edge lengths among all possible triangulations, maximal support path must lie on the lines of the Delaunay triangulation of the sensors (Fig. 5). Delaunay triangulation of the sensor nodes is constructed and considered as a weighted graph, where the weight of each edge is the length of that edge. The maximal breach path is found through an algorithm that uses breadth first and binary searches [23, 26].

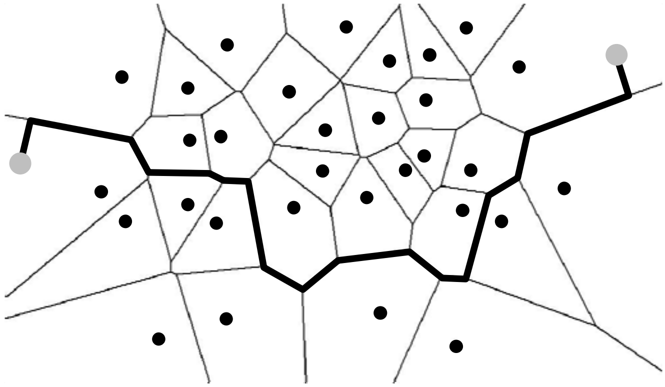


Fig. 4. Maximum breach path in a sensor network and its connection to Voronoi diagram

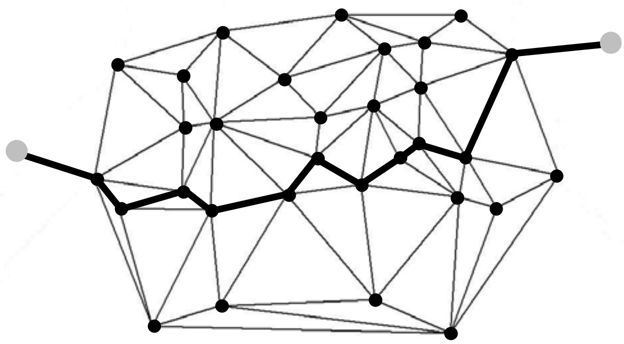


Fig. 5. Maximum support path in a sensor network and its connection to Delaunay triangulation

4.2 Healing the Holes

Having detected the coverage holes, the sensors must be relocated in order to heal the holes. For this, we classify the Voronoi-based solutions based on the sensor types used in the network: (1) Static sensor networks, (2) mobile sensor networks, and (3) hybrid sensor networks, where a combination of static and mobile sensors is deployed. For static sensor networks, new sensors are added. For mobile and hybrid networks, however, existing sensors moves to heal the holes.

Static Sensor Networks

To the best of our knowledge, there are two suggestions to deploy an additional sensor to heal the holes in a static sensor network. Gosh [9] proposes that for each Voronoi vertex, one node should be added to heal the coverage hole around this Voronoi vertex. As Fig. 6 shows, to heal the hole around Voronoi vertex v_2, the target location p_1 lies on the bisector of the angle $v_1v_2v_3$ and $d(s, p_1) = \min\{2R, d(s,v_2)\}$, where d is the

Euclidean distance and R is the sensing radius of the sensors. Wang *et al.* [39], however, deploy only one mobile node to heal the coverage hole of a Voronoi cell. As illustrated in Fig. 6, the target location p_2 lies on the line connecting the sensor node and its furthest Voronoi vertex (v_4 here) and $d(s, p_2) = \max\{\sqrt{3}R, d(s,v_4)\}$.

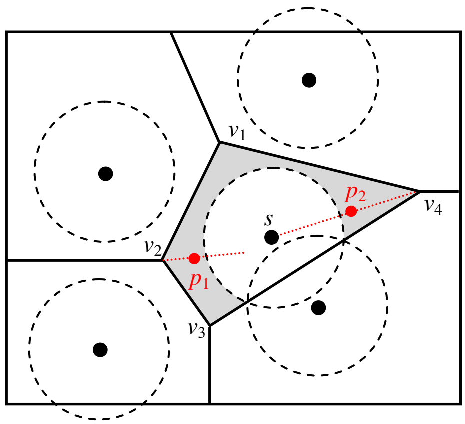


Fig. 6. Deploying an additional sensor to heal the hole in a static sensor network

Mobile Sensor Networks

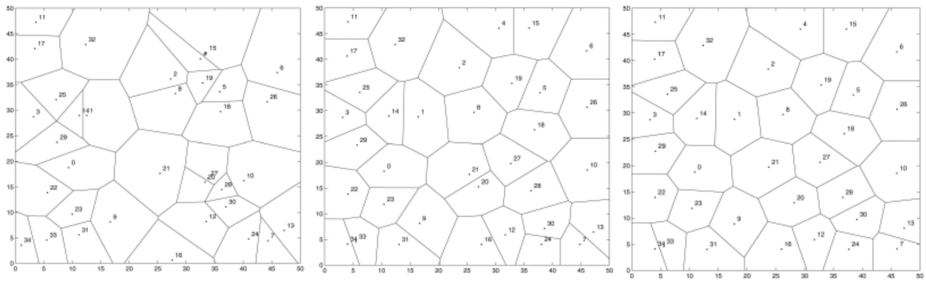
In mobile sensor networks, all sensors have the ability to move in order to heal the holes. Wang *et al.* [40] proposes three Voronoi-based strategies for this movement: Vector-based (VEC), Voronoi-based (VOR), and Minimax. They all are iterative approaches and gradually improve the coverage of the sensor network.

VECtor-based Algorithm (VEC)

VEC pushes sensors away from a densely covered area. It imitates the electromagnetic force that exists between two particles: if two sensors are too close to each other, they exert a repulsive force. By knowing the target area and the number of sensors, an average distance between the sensors, d_{avg} can be calculated beforehand. If the distance between two sensors s_i and s_j is smaller than d_{avg} and none of their Voronoi cells is completely covered, the virtual force pushes them to move $(d_{avg} - d(s_i, s_j))/2$ away from each other. However, if one of the sensors completely covers its Voronoi cell, and so it should not move, then the other sensor pushes $(d_{avg} - d(s_i, s_j))$ away.

In addition to the repulsive forces between sensors, the boundaries also exert forces to push sensors that are too close to the boundary inside. If the distance of the sensor i, i.e., $d_b(s_i)$, from its closets boundary is smaller than $d_{avg}/2$, then it moves $(d_{avg}/2 - d_b(s_i))$ toward the inside of the network.

Note that movements of the sensors change the shape of the Voronoi cells, which may result in decreasing the coverage in the new configuration. Thus, the sensors move to the target position only if their movement increase the local coverage within their Voronoi cell. Otherwise, they take the midpoint position between its current and target positions, as the new target position, and again check the improvement, and so on. This process is called movement adjustment). Fig. 7 shows an example of using VEC algorithm.



Round 0 Round 1 Round 2

Fig. 7. An example of using VEC algorithm to move the sensors [40]

VORonoi-based Algorithm (VOR)

Unlike VEC algorithm, VOR is a pulling strategy so that sensors cover their local maximum coverage holes. In this algorithm, each sensor moves toward its furthest Voronoi vertex till this vertex is covered (Fig. 8). The movement adjustment mentioned for VEC is also applied here. Furthermore, VOR is a greedy algorithm that heals the largest hole. However, after moving a sensor, a new hole may be created that is healed by a reverse movement in the next iteration, so it results in an oscillation moving. An *oscillation control* is added to overcome this problem. This control does not allow sensors to move backward immediately: Before a sensor moves, it first checks if the direction of this moving is opposite to that in the previous round. If so, it stops for one round to see if the hole is healed by the movement of a neighbouring sensor. Fig. 9 shows an example that moves the sensors based on VOR algorithm.

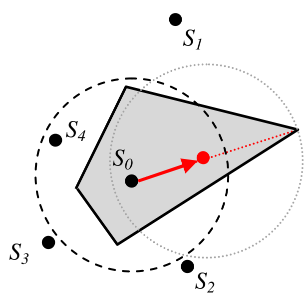


Fig. 8. Movement of a sensor in VOR algorithm

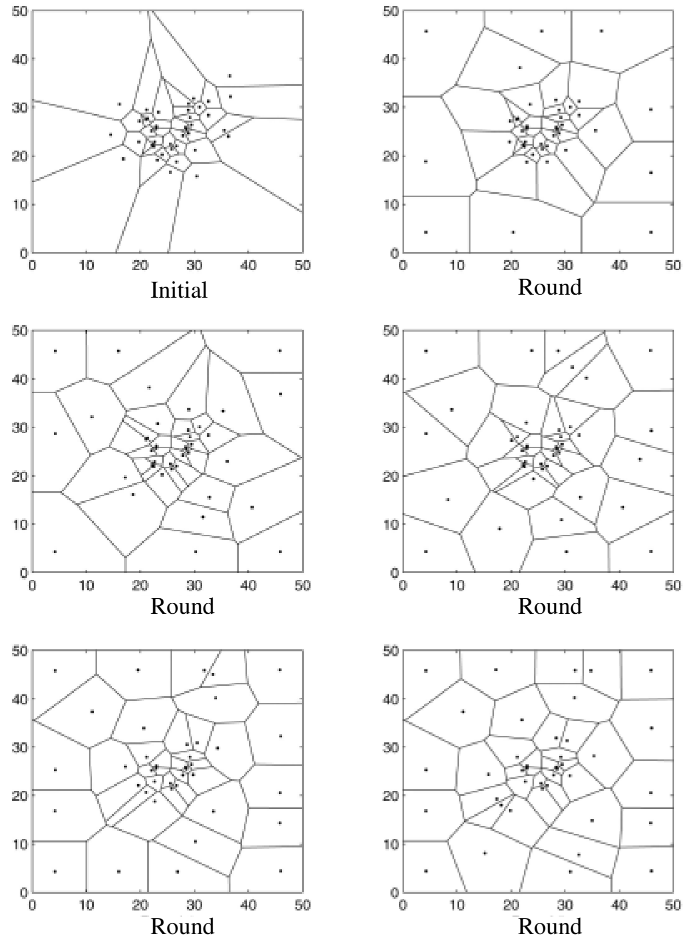


Fig. 9. An example of using VOR algorithm to move the sensors [40]

Minimax Algorithm

This algorithm is based on the fact that when the sensors are evenly distributed, a sensor should not be too far away from any of its Voronoi vertices. In other words, the disadvantage of VOR algorithm is that it may result in a case where a vertex that was originally close becomes a new farthest vertex. The MiniMax algorithm solves this by choosing the target location as the point inside the Voronoi cell whose distance to the farthest Voronoi vertex is minimized. This point, which is called *Minimax* point, is the center of the smallest enclosing circle of the Voronoi vertices and can be calculated by the algorithms described in [24, 32, 41]. Minimax algorithm has some advantages. Firstly, it can reduce the variance of the distances to the Voronoi Vertices, resulting in more regular shaped Voronoi cells, which better utilizes the sensor's sensing circle. Secondly, Minimax considers more information than VOR, and it is more conservative. Thirdly, Minimax is more “reactive” than VEC, i.e., it heals the hole more directly by moving toward the farthest Voronoi vertex.

Hybrid Sensor Networks

In a hybrid sensor network, having detected a hole around a static sensor, a mobile sensor moves in order to heal this hole. The location to which the mobile sensor should move is computed similar to the solutions proposed for the static networks in section IV.B.1. Then, the static sensor requests the neighbouring mobile sensors to move to the calculated destination. Each of the mobile sensors that have received this request calculates the coverage holes formed at its original location due to its movement. It decides to move if the new hole is smaller than the hole size of the requesting static sensor. It is noted that since movements of the mobile sensors may create new (but smaller) holes, this solution is an iterative procedure. More discussion on this movement and its technical considerations (e.g., bidding protocols) can be found at [9, 39].

4.3 Node Scheduling

As it was mentioned earlier, energy is an important issue in sensor networks. Thus, strategies to save energy are of most interest in this regards. A relevant case to save the energy is turning temporarily some sensor nodes to sleep mode in the multi-covered areas. This is also important to avoid other problems (e.g., the intersection of sensing area, redundant data, and communication interference), in areas with a high density of sensor nodes [21]. Different methods have been proposed for this problem [29, 36].

Augusto *et al.* [21] proposed a Voronoi-based algorithm to find the nodes to be turned on or off. The Voronoi diagram of the sensor nodes is constructed. Each Voronoi cell represents the area that the corresponding node is responsible for. The sensors whose responsible areas are smaller than a predefined threshold are turned off. By updating the Voronoi diagram, the neighbours of that sensor become responsible for that area. This process continues until there is no node responsible for an area smaller than the given threshold.

4.4 Other Challenges

This section shortly introduced more complicated issues in sensor coverage problem that can be dealt using Voronoi diagram and Delaunay triangulation.

K-Coverage Sensor Networks

In some applications, such as military or security control, it is required that each point of the region is covered by at least k (k>1) sensors. Among different solution proposed in the literatures [43], So and Ye [33] has developed an algorithm based on the concept of *Voronoi regions*. Suppose that $P=\{p_1, p_2, \ldots, p_n\}$ is a set of n point in $\mathbf{R}^n$. For any subset U of P, the Voronoi region of U is set of points in $\mathbf{R}^n$ closer to all points in U than to any point in P-U. The proposed algorithm can check the k-coverage for the area, but developing the algorithms to heal the holes is still an open question.

Sensor Networks with Various Sensing Ranges

So far, we have assumed that all sensors are identical. In reality, however, a sensor network could be composed of multiple types of sensors with different specifications, including their sensing range and sensing model (e.g., circular, ellipsoidal or irregular sensing model [3, 33]). Weighted Voronoi diagram is a solution in such cases to examine the coverage quality of the network (Fig. 10) [33]. However, to the best of our knowledge, the movement strategies have not been researched deeply for such heterogeneous sensor networks.

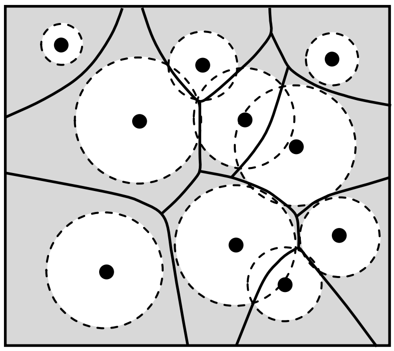


Fig. 10. Using weighted Voronoi diagram to examine the coverage quality of a sensor network with various sensing ranges

Directional Sensor Networks

Coverage determination for directional sensor networks (i.e., networks composed of sensor with limited field of views) is a practical area of research. Adriaens *et al.* [2] has extended the research done in [23, 26] and developed a Voronoi-based algorithm to detect the worst-case coverage (maximal breach path) in such networks.

Sensor Networks in a 3D Environment

The approaches mentioned in this paper assume that a sensor network is deployed in a 2D flat environment (i.e., a 2D Euclidean plane). However, this assumption oversimplifies sensor network reality. The real world environment is mostly 3D heterogeneous filed and contains obstacles (Fig. 11). Hence, 3D sensor networks have considerable interest in diverse applications including structural monitoring networks and underwater networks [17]. In addition to the form and the relief of the sensor network area, various obstacles may prevent the sensors from covering an invisible region or communicating data between each other.

Several algorithms have been proposed for the coverage problem of 3D sensor networks [4, 7, 17]. The algorithms presented here can be extended to use 3D Delaunay triangulation and Voronoi diagram for coverage determination and optimization of such sensor networks [10, 20, 22]. There are also suggestions to use Delaunay triangulation and Voronoi diagram when the environment contains obstacles [16]. Although these extensions are interesting in some applications, they may have deficiencies for the geographical fields, because they consider 3D

Euclidean filed and man-made obstacles, e.g., walls. Real world environment, however, is a 3D heterogeneous filed full of man-made and natural obstacles. Even, the terrain could play the role of an obstacle in this case. Using capabilities of geographical information systems (GIS) seems a promising solution in this regard, which has not been investigated. It can provide the information (e.g., digital terrain models) or spatial analyses (e.g., visibility analysis) required to evaluate and optimize the sensor networks installed in the nature environment. Hence, 3D Delaunay triangulation and Voronoi diagrams present interesting solutions for the sensor network modeling and optimization in 3D environment. However, their application is not straightforward and several challenging conceptual and implementation problems should be addressed.

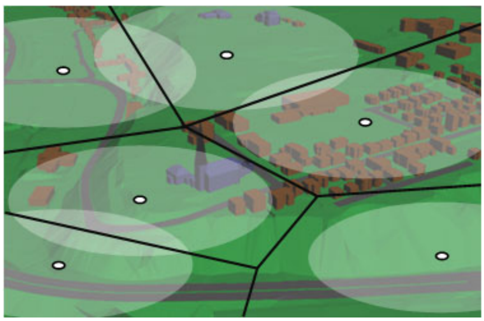


Fig. 11. A sensor network in a 3D environment with various obstacles. The superimposed 2D Voronoi diagram cannot determine the network coverage

5 Proposed Approach for a Realistic Sensor Network Deployment

Although efficient sensor deployment for maximum network coverage has been extensively addressed in the literatures (sections 3 and 4), they are not adequately adopted to consider the reality of the terrain and the environment where the sensor networks are deployed. The main reasons are:

- Most of the existing solutions suffer from the lack of integrating environmental information with sensor network deployment algorithms. They do not consider the form and the topography of the area covered by the sensor network as well as various existing obstacles that may prevent the sensors from covering the whole area or allowing data communication between sensors. To carry out a realistic sensor placement scheme, it is necessary to involve the environmental information that affects sensor performance and network coverage.
- The sensor network region of interest may change over the sensing experiments. For instance, in a battlefield all parameters of the study area may rapidly change. In urban areas, new constructions may happen, urban facilities may be added or removed or changes may occur in land cover and land use information. These changes may significantly affect the sensor network coverage. Furthermore, characteristics of sensor platforms may change during the sensing steps. For example, fluctuation of the battery power for each platform decreases the sensing

range of nodes, so the network arrangement must be modified to stay in good network performance. These changes must be considered by the network and the development methods must be adopted to deal with them.

For establishing a realistic sensor network, we propose an innovative sensor placement method using Voronoi-based optimization methods integrated with terrain information and realistic sensors models. For that purpose, an optimization process is coupled to a Geographical Information System (GIS) for integrating spatial information, including man-made (buildings, bridges, etc) or natural objects. Moreover, the functions and capabilities available in GIS serve more facilities in sensor network deployment. Visibility, line of sight and viewshed analysis are examples of GIS operations that will be used in this regard. Finally, we deploy a dynamic geometric data structure based on Voronoi diagram in order to consider the topology of the sensor network and its dynamics (e.g. inserts, move, delete). In short, our approach focuses on definition and implementation of a framework that integrates environmental information for optimal deployment of sensor nodes based on a geometric data structure (e.g., Voronoi diagram) and optimization algorithms.

A GIS aided simulation platform based on a geometric data structure is used to reduce the coverage holes and to make an optimum sensor network deployment. This is done by using the functionality of a GIS to locate environmental objects such as buildings, vegetations, and sensor nodes in their accurate positions. It also uses other environmental information such as Digital Terrain Models (DTM) to get more reliable results. DTMs are very important issues to be included in the realistic modeling of sensor placement, which have not been considered in most of the previous works. Using GIS helps the deployment process in terms of analyzing the visibility between the sensors (viewshed) and line of sight for sensing area of each sensor in the network.

The proposed framework consists of three major parts including a spatial database (GIS), a knowledgebase and a simulation engine, based on Voronoi diagram (Fig. 12). The spatial database is implemented using a GIS, where different environmental elements organized as different layers, such as man-made and natural obstacles (e.g., streets, building blocks, trees, poles and terrain topography). Another layer will contain the coverage, which is calculated in different steps of the sensor network placement process. An extra layer is defined to keep the sensors positions. These various GIS layers may be updated during the sensing mission considering the fact that the coverage layer may change following the changes in the environmental information layers or sensor nodes positions. All attributes are defined in this database and all metric and topologic operations are exported based on the analyses that are carried out in this database. Other GIS processes such as visibility and viewshed analyses are done in this database.

The second component is the knowledgebase. All environmental and network parameters are used to define basic rules and facts that are stored in this knowledgebase. The knowledgebase is used by a simulation platform for sensor network deployment. The simulation engine consists of a local optimization algorithm based on Voronoi diagram. A reasoning engine will help to extract the appropriate commands to move or delete existing sensors or add new sensors in the network to satisfy the optimum

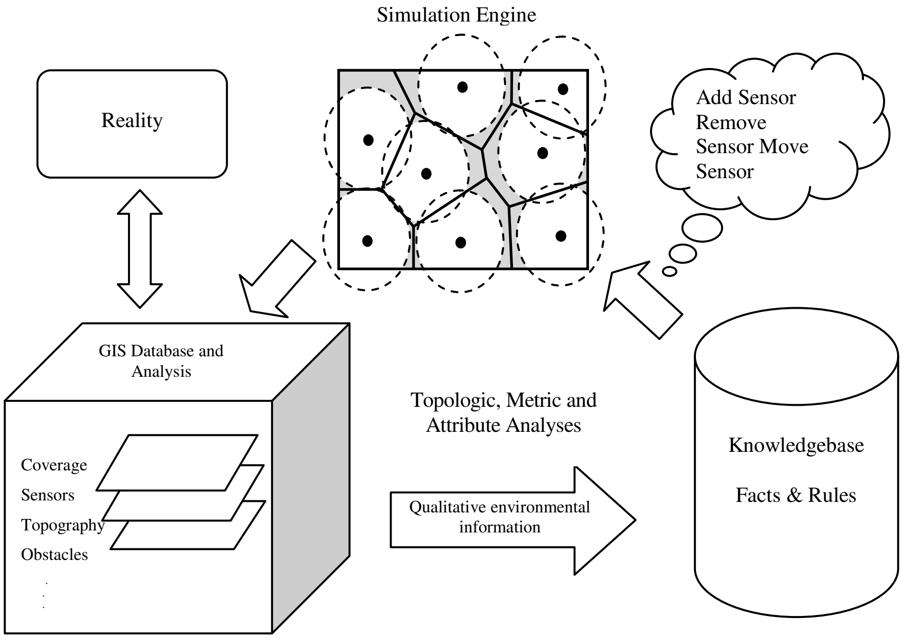
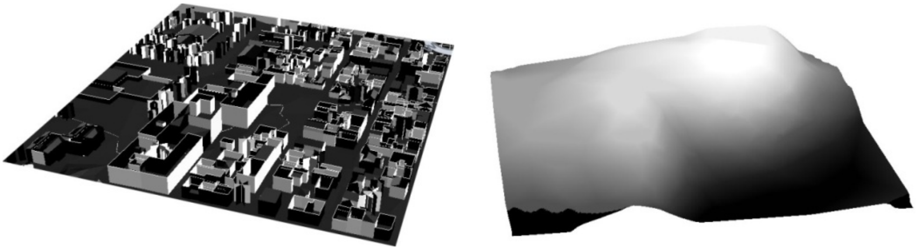


Fig. 12. The proposed framework

coverage. In fact, the optimization algorithm tries to relocate the sensors based on the defined rules in this knowledgebase. Both the database and the knowledgebase components are in relation with the simulation engine as shown in the figure 12.

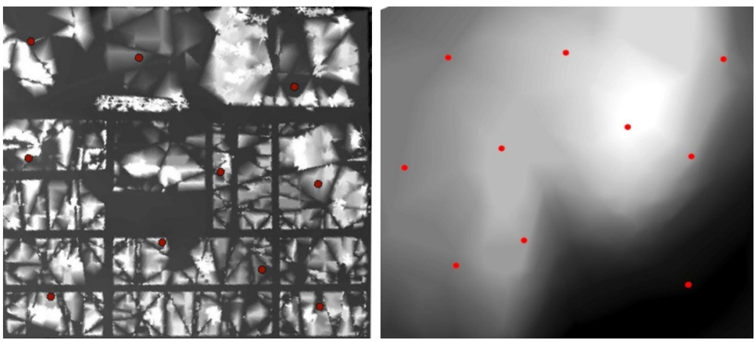
6 Implementation of the Proposed Approach for Two Case Studies

For evaluation purpose, the proposed sensor deployment approach has been used in two case studies. The first case consists on deploying a sensor network in an urban area, which is a small part of Quebec City (Fig. 13a). In the second case study, we consider a sensor network in a natural area is a small part of Montmorency Forest located in the north of Quebec City (Fig. 13b). Initially, the study areas were covered by 10 sensors with sensing range of 50 meters for both maps. The sensors can rotate -90° to 90° vertically and 0° to 360° horizontally. Initially, the sensors were considered to be randomly distributed in both natural and urban study area. For the urban data set, we suppose that the sensors are deployed in a network to monitor activities in a small part of a city. Assuming this, the sensors could be video cameras or optic sensors with the ability to rotate in 2D or 3D orientations, installed a few meters above the ground. This assumption is necessary to better consider the presence of different obstacles in the sensing area.



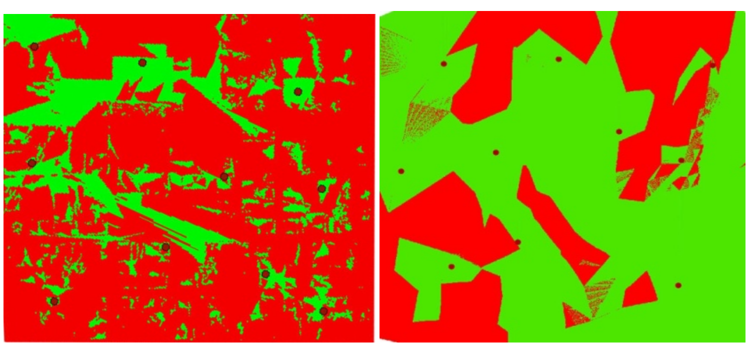
(a) (b)

Fig. 13. The study areas: (a) a small part of Quebec City (urban area) and (b) a small part of Montmorency Forest in Quebec (natural area)



(a) (b)

Fig. 14. Initial positions of the sensors on the DTM: (a) urban area (b) natural area

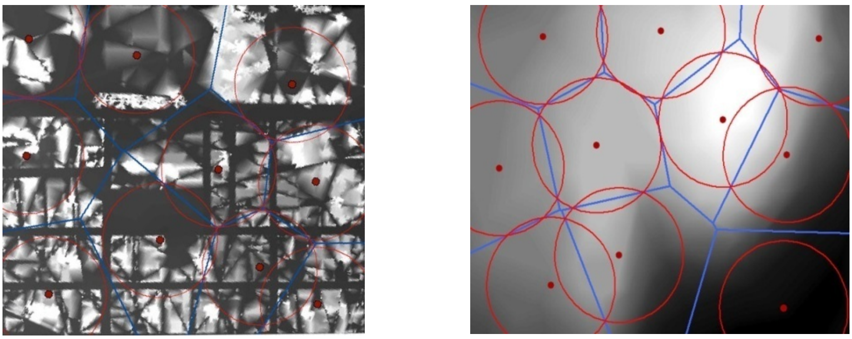


(a) (b)

Fig. 15. Viewshed of the first sensor deployment: (a) urban area (b) natural area. Green regions are visible and red regions are invisible.

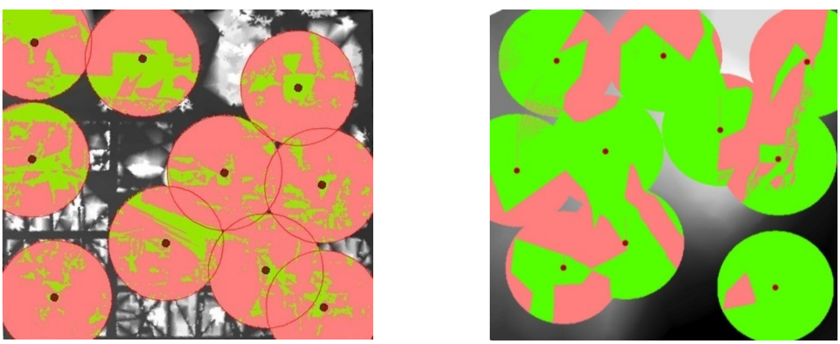
Fig. 14a and 14b show the initial position of the sensors on the DTM, of the urban and natural areas respectively, which result in viewsheds of the sensors in the environments (Fig. 15a and 15b).A pixel is assumed to be visible if it is observable by at least one sensor.

A 50 meter buffer around each sensor shows its sensing range. On the other hand, as explained in section 4, it is desired that each sensor node cover its Voronoi cell. Therefore, as shown in Fig. 16a and 16b, the current configuration is not optimal because there are areas that are covered by none of the sensors. Overlaying the buffers and the viewshed maps, the visible area in the sensing field of each sensor node is obtained (Fig 17a and 17b), which are 23% for the initial deployment of the sensors in the urban area and 66% in the natural area. We called this overlaid area, the coverage of each sensor. While, the visibility, means all of the area which have the possibility to be observed by the sensor nodes without considering the sensing range of the sensors.



(a) (b)

Fig. 16. Sensor's positions and their related sensing buffer and Voronoi cells in the initial deployment: (a) urban area (b) natural area

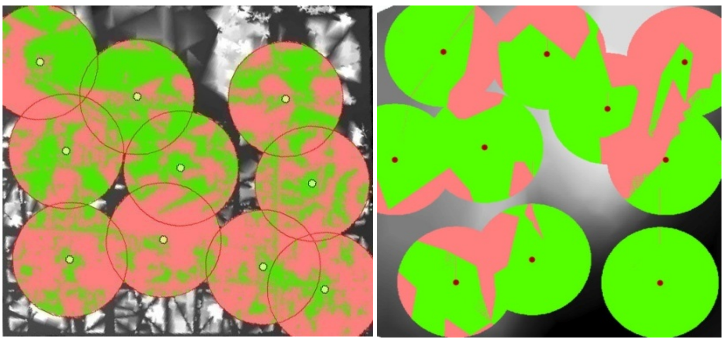


(a) (b)

Fig. 17. The covered regions in the sensing field of each sensor node in initial deployment: (a) urban area (b) natural area. Green regions are visible and pink regions are invisible.

To increase the covered area, the VOR algorithm (section 4) is used: the sensors were moved toward the farthest Voronoi vertex, but with this restriction that the sensor stops if it reaches a position with a higher elevation than its current position.

This constraint is an extension to the VOR algorithm that allows us to better consider the topography of the terrain and the presence of various obstacles in the sensing area. This consideration will help us to significantly improve the spatial coverage of the sensor network in both case studies and also prove our initial hypothesis. Fig. 7a and 7b show the result of this movement. As Table 1 indicates, both of visibility and coverage have been relatively improved in both urban and natural areas. In urban area, the visibility has been increased 12% as well as 4% in natural area. In terms of coverage, in urban area there is 14% of coverage improvement and in natural area we can see 5% of coverage improvement.



(a) (b)

Fig. 18. The covered regions in the sensing field of each sensor node in second deployment (green regions are visible and pink regions are invisible)

Table 1. Visibility and coverage before and after optimization

Case		Visibility (no. of pixels)	Visibility (%)	Coverage (no. of pixels)	Coverage (%)
Urban area	Before optimization	23458	22	16810	23
	After optimization	37463	34	25174	37
Natural area	Before optimization	60250	67	40806	66
	After optimization	63995	71	43952	71

7 Discussion and Conclusions

This paper was focused on the coverage problem of geosensor networks. First, we have presented an overall review of the existing approaches for the optimization of the coverage of geosensor networks. Especially, algorithms that use Voronoi diagram and Delaunay triangulation were intensively investigated. As discussed in the paper, most of these methods oversimplify the coverage problem and they do not consider the characteristics of the environment where they are deployed. Spatial coverage of a sensor network is significantly related to the spatial distribution of the sensors in the environment. The coverage optimization algorithms aim at distributing sensors in the environment so that the maximum coverage is obtained.

Our extensive survey in the literature revealed that Voronoi diagram and Delaunay triangulation are well adapted for abstraction and modeling of sensor networks and their management. However, their applications are still limited when it comes to the determination and optimization of spatial coverage of more complex sensor networks (e.g., sensor networks with the presence of obstacles).

In order to overcome the limitation of these methods, a novel approach based on Voronoi diagram has been proposed in this paper. The algorithm considers spatial information in senor network deployment and coverage optimization. In order to evaluate the proposed method, two case studies were presented in the paper. The case studies provide interesting information on different challenges in the sensor network deployment both in urban and natural areas. The preliminary results obtained from these experimentations are very promising. As presented in the last section, we have observed a considerable improvement in the spatial coverage of the geosensor networks in both cases. These results are a part of an ongoing research project and more investigations will be carried out in order to improve the quality and the performance of the proposed method in the future.

Acknowledgment. This research is supported by the project entitled Integrating developmental genetic programming and terrain analysis techniques in GIS-based sensor placement systems by the Canadian GEOIDE Network of Centres of Excellence.

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