A Novel and Efficient Algorithm for Deploying Mobile Sensors in Subsurface

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Abstract

The demand for oil is growing steadily from emerging and developing economies while oil field discoveries continue to decline. Therefore the gap between demand and supply will increase with time. Subsurface Exploration deals with extracting valuable hydrocarbons from oil wells. Due to its hazardous nature, it's one of the most difficult fields to carry experimentations on. Uncertainties associated with this field are result of various factors such as lack of information regarding location, size and spread of natural resource. In order to handle above listed factors, mobile wireless sensors seems to be a promising paradigm for increasing productivity and throughput by serving as intelligent investigators. At the time of this listing, none of the researchers have proposed the deployment of mobile wireless sensors in the oil fields. Therefore, this work contributes a unique strategy that could deploy mobile sensors in the subsurface so as to get real time information which otherwise is not possible. Moreover, the proposed algorithm provides efficient coverage and connectivity metric. Also, a mathematical model has been presented along with its comparison with other existing node placement strategies in other related fields and it is found that our algorithm provides better coverage and connectivity.

Keywords: Wireless sensor networks, Subsurface exploration, Sensor deployment

1. Introduction

Subsurface exploration [Juneja, Dimple. et al., (2009)] is the process of extracting hydrocarbons available beneath earth crust. The figures [CIA] presented by Central Intelligence Authority (CIA) reflects the facts that increase in demand of hydrocarbons is directly proportional to the consumption of hydrocarbons. The available facts [AEC (2008)] indicate that only 30% (approximately) of oil is recovered from an available field & rest of 70% remains un-extracted due to lack of information or various other factors, such as amount remaining, pressure, temperature & other real time conditions. To keep pace with increased demands as well as consumption, oil companies are in never ending pursuit for improving the production of existing wells with the help of latest technologies. In fact available literature [Roger M. et al., (2004), Colibrys, CNBC] reveals the fact that very few researchers have spent little time looking at the more recent work from other fields. One example of this is the lack of wireless sensor networks [David Culler, et al., (2004), WSN] within the community of subsurface exploration. There are many properties of sensors such as intelligent sensing, collection and processing of data,

make them well suited to uncertain environments. The adoption of Mobile Sensors as architectural elements enables us to achieve the desired delegated goal of enhanced oil recovery which in turn demands the formulation and development of a novel sensor deployment strategy in subsurfaces.

Usually, static sensors [Eisenman, S. B., et al., (2006), Ghosh, A. (2004)] are being used, which do not have any kind of locomotive capability, whereas mobile sensors may be deployed for better performance [B. Liu, et al., (2005)]. A mobile sensor network [Ghosh, A. (2004), X. Du, et al., (2005)] comprises of a distributed collection of nodes, which in addition to sensing, computation and communication abilities, is also possessed with locomotion capabilities. Deploying mobile sensors result in increased network coverage, better routing performance, self deployment and self reconfiguration. This research proposes deployment of mobile sensor in subsurfaces since reconfiguration of nodes depending on real time conditions shall be far more easy and attainable.

The paper is structured as follows: Section II discusses the motivation of deploying mobile sensors in oil fields. Section III throws light on the light of work of researchers who proposed deployment strategies for wireless sensors in other related fields Section IV presents the proposed strategy along with its pros and cons. Also comparison of our strategy with others is being presented. Finally, section V concludes the paper and illustrates the future work.

2. Motivation of Deploying Mobile Sensors in Oil Fields

Advances in Micro-Mechanical Systems (MEMS) have allowed integration of sensors, actuators, mechanical elements and wireless communication on a common silicon substrate with the help of micro-fabrication. These integrated units are low-cost and small form-factor embedded systems called sensor nodes [Sohrabi, K. . et al., (2000), Estrin, D. , et al., (1999)]. Wireless sensors leading to a robust and scalable WSN are being successfully used for energy management [Bin Lu, et al., (2005)], medical monitoring [Virone, G. , et al., (2006)], battlefield management / surveillance [Tatiana Bokareva, et al., (2006)], habitat monitoring [Alan Mainwaring, et al., (2002)], and security systems [Nils Timotheus, et al., (2008)] and so on. Although the proposals [AEC (2008)] have been invited for the deployment of sensors in oil fields but none have succeeded in deployment of sensors in subsurface exploration. The need for self-effacing and remote monitoring is the main motivation for deploying a sensing and communication network consisting of a large number of these battery powered sensor nodes.

3. Background

Traditionally in WSN network application, sensors are deployed with aim of monitoring a specified area. In certain applications it was always easy to select sites where sensors could have been placed, e.g. sensors placed in a building for firefighting [Sammarco, J.J. , et al., (2007)] purpose or to monitor intrusion detection and such a deployment is termed as deterministic deployment. But in non-deterministic deployment like habitat monitoring [Alan Mainwaring, et al., (2002)] in hostile locations, large numbers of sensors are simply scattered via air drop with the hope that they connect with each other and start passing data within themselves. For both strategies, various, algorithms [Estrin, D. , et al., (2001), Akkaya, K. ., et al., (2005), Wang, Y.C. , et al., (2005)] have been developed ensuring the coverage [Huang, C.-F., et al., (2003), Bai, X. , et al., (2006)] and connectivity [Bai, X. , et al., (2006), Wang, X. , et al., (2003)] discussed in the following subsections. However, the literature reveals the fact that neither of the strategies is suitable enough to be employed in subsurface. Therefore, an optimal deployment of finite number of sensors in oil fields that are able to communicate efficiently is in high demand.

3.1 The problem statement: Coverage and Connectivity

The coverage property [Zou, Y., et al., (2005)] checks that sensors being deployed are adequately covering all data points which are to be sensed or monitored whereas Connectivity checks that these sensors are not placed far apart such that they are unable to communicate with each other. The section discusses various mathematical models employed for efficient coverage and connectivity in various domains.

Researchers [Zhang, H., et al., (2004), Xiaorui Wang, et al., (2003)] proved that for a finite sensor density in k-coverage, $c \geq 2r$ is a necessary and sufficient condition for coverage to imply connectivity where "r" is sensing range of a sensor or the distance to which a sensor can monitor desired activities, while "c" is the communication range of the sensor. Also,   k-coverage with $k > 1$ affords some degree of fault tolerance and is able to monitor all points so long as no more than $k - 1$ sensors fail.

Xu & Sahni [Xiaochun Xu, et al., (2007)] introduced an Integer Linear Programming (ILP) formulation assuming a set of modalities such as temperature, sound, levels of different gases, radioactivity etc. at each location. This formulation for cost calculation is fine for traditional applications of Wireless Sensors. However, the same cannot be applied directly in a subsurface as it comprises of relatively harsh vibration, temperature and corrosive

environments. Since, sensor technology is used in a wide range of applications and in various different markets; therefore, these can be deployed in either a phased or iterative manner. This work while making use of pipeline robot developed by Iyengar and his team in the Robotics Research Lab [Iyengar] at Louisiana State University for initially deploying the sensor in area just near well head and activating them to communicate with each other in the first phase, proposes to carry out the second phase of deployment inside subsurface wherein the valuable and critical information governed by the real time factors is inferred with the help of deployed sensors and hence can be utilized for improving the quality and quantity of production. The proposed deployment strategy is discussed in detail in the upcoming section.

4. The Proposed Deployment Strategy

The proposed algorithm adopts an incremental deployment strategy that makes use of information provided by previously deployed nodes and is inspired from the works of Andrew et al. [Howard, A., et al., (2002)] who made an attempt to systematize non deterministic deployment, by using the information gathered from previous phase. However, this section proposes a novel deployment algorithm considering the harsh conditions and real-time environment prevailing in subsurface. For instance, in contrast to the author's presumption of homogeneous nodes, this work focuses on heterogeneous nodes. The proposed algorithm aims to maximize both the network coverage as well as the connectivity parameter. Before presenting the algorithm in detail, following are the key considerations that are to be assumed as is for convenience and simplicity.

4.1 Key Assumptions

The proposed algorithm has been developed keeping the following three factors as it key assumptions.

- **Heterogeneous nodes:** The objective is to dynamically guide the sensors to its final location. The increased stability and appropriate location of the sensors helps reducing the number of measurement points required to monitor precisely a surrounding area and consequently reduce the cost of a survey. In order to measure the modalities present within subsurface, various kind of sensor nodes such as temperature sensor, pressure nodes, acoustics nodes, flow nodes etc. will be deployed.

- **Geometrical Considerations:** It is assumed that the gross topology within the subsurface remains static while the network is being deployed. This implies that the geo obstacles present do not displace during this course of time. The major design challenge that would be simplified i.e. the sensor network be reconfigured, expanded, or otherwise modified without a loss in performance. The static configurations and topologies are conducive to scalability in terms of power and bandwidth usage, congestion control, and overall network robustness to disruptions.

- **Mesh Communication**: Assuming that each sensor has a sensing radius, "*r*" and it can only sense the environment and detect events within its sensing area, which is the disk of radius "*r*" centered at the sensor. A point is said to be covered by a sensor if it is located in the sensing area of the sensor. The sensor network is thus partitioned into two regions, the covered region, which is the region covered by at least one sensor, and the uncovered region, which is the complement of the covered region. A communication is said to be mesh or full if it detects the events happening in both covered and uncovered area. Also, it is assumed that all nodes after being deployed in the network can communicate with remote base-station on which the deployment algorithm is executed.

On the basis of these three assumptions, following section presents a high level view of the proposed algorithm.

4.2 High Level View

The algorithm primarily comprises four phases namely, Initialize, Choose, Allocate and Enforce. The flow of information among various phases is as depicted in Fig.1 and the key functionality of the phases is delineated in Table 1. It may be noted that the nodes are either in waiting, active or deployed state and conditions for each state change is explained with the help of Fig.2.

The algorithm iterates through the Choose, Allocate and Enforce phases, terminating only when all nodes have been deployed. The phases are explained in the following subsections.

1) Initialize
Initialize is the very first phase of the algorithm and initially all nodes are set to waiting state except for one whose state is set to active and is considered as a node ready to be deployed.

2) Choose
This phase determines the next deployment location, or goal and the desired goal is usually the one that either maximizes the coverage metric i.e. max(coverage_metric) where coverage metric is computed at a location 'l' for

a modality 'm' by maintaining an allocation grid. An Allocation Grid is 2D arrangement of the total area that is likely to be covered. Each cell of the grid is defined as unallocated, allocated or unknown. An unallocated cell implies that it contains no obstacles whereas an allocated cell state implies that it can pose an obstacle. Here obstacle implies a node, which has been deployed in that particular cell. It's being termed as obstacle since it might obstruct the deployment of other nodes to farther cells. In case of non-availability of information about the state of a cell, it is treated as an unknown location i.e. the unknown location cannot be chosen as the next desired destination.

Now, each deployed node communicates its sensing range say 'r' implying that the upcoming active node shall be deployed in a cell which is not only set as unallocated but also satisfies the relation $c \geq 2r$, where 'c' is the communication range ensuring the condition *max(coverage_metric)*. Depending upon the information gathered, the appropriate cell is chosen and the location of the same is forwarded to the next phase.

3)   Allocate

The main aim of the phase is to assign the location chosen during chose phase to a waiting node. The state of the node changes from waiting to active. The phase allocation is simple in case the desired location can be reached unobtrusively. However, if there are nodes already deployed on the path to be followed by the active node, these deployed nodes act as obstruction and such obstructions become increasingly likely to happen as the size of the network increases. This makes

 "Allocate" the most important and complex phase of deployment. Now, in order to overcome the stated complexity this work proposes a novel mechanism which allows goal swapping i.e. an active node swaps its own goal with the deployed node leading to the state exchange between two nodes. This implies that the active node acquires the location of deployed node and the deployed node becomes the new active node.

4)   Enforce

During this phase, active nodes are ultimately deployed to their goal locations. Node deployment is a consecutive process i.e. only one node remains in active state while all other are either waiting or deployed. Since there is only one node in motion at any given point in time and the goal assignment ensures that each successive goal is unobstructed, there is very little possibility of interference between nodes. However, this deployment process is quite slow. The execution time is proportional to the sum of the distances traveled by the active nodes which in turn is equal to the distance a single node would have traveled if there were no obstructions. As the area covered by the deployed network becomes larger, nodes will have to travel farther and farther and hence it is expected that execution time will increase with the number of deployed nodes.

The upcoming section presents the working algorithm, flowchart of the proposed work, followed by an example of node replacement.

4.3 Working Algorithm, Flowchart & Mathematical Model

4.3.1 Algorithm for the proposed deployment strategy:

Input required for the algorithm:

- 	*node(i): which represents the ith node to be deployed*
- 	*g_1: which represents the randomly selected goal where the node(1) is to be deployed.*

 1) initialize: set status [node(i)] =waiting $\forall i \in \{1, 2, \ldots \ldots m\}$

 2) set status [node(1)] =active

 3) deploy node(1) at goal g_1

        set status[node(1)] =deployed

 4) *repeat*

 5) collect information from node(i) $\forall i \in \{1, 2, \ldots \ldots m\}$

        calculate new goal g_j $\forall j \in \{2, 3, \ldots \ldots m\}$

 6) *if* node(i) $\forall i \in \{1, 2, \ldots \ldots m\}$ lie on linear path between point of deployment and g_j *then*

 7) set status [node(i)] = active $\forall i \in \{1, 2, \ldots \ldots m\}$

              redeploy nodes

 8) deploy node(i+1)

 9) set status[node(i+1)], status[node(i)] = deployed

10) *else*

11) deploy node(i+1) to goal g_j

12) set status[node(i+1)] = deployed

13) *end if*

14) *until* status[node(i)] =deployed $\forall i \in \{1, 2, \ldots \ldots m\}$

15) stop

4.3.2 Flowchart:

Refer to Figure 3 after reference section

An Example

If *node(i)* obstructs the path to *node(i+1)* deployment location [Fig 4(a)], then *node(i)* can be redeployed to *node(i+1)* location, while *node(i+1)* will occupy the previous location of *node(i)*.

Since all nodes are assumed to be equivalent, this goal-swapping makes no functional difference to the network. For complex environments, with many obstructions, this resolution strategy may need to be applied recursively, so that

$$\text{node(j-1)} \sim\text{replaces}\sim \text{node(j)} \quad \forall j \in i-1, i-2, \ldots \ldots, 1$$

[Fig 4(b)]

here,

status {node(i)}=active

i.e. it's being deployed in the current iteration

The proposed mechanism executes in an iterative manner oozing the nodes from a central location to an uncovered location. In addition, as the nodes spread throughout the environment, the same nodes will tend to remain on the edge of the network.

4.3.3 Mathematical Model

The proposed algorithm with the mentioned assumptions and constraints ($c \geq 2r$) would lead a 2D allocation grid as shown in Fig.5. The network is formed by placing several horizontal r-strips. The paper [Kar, K., et al., (2003)] defines r-strip as a string of r-disks placed along a line such that the distance between the centers of any two adjacent r-disks is r. Sensors with a sensing/transmitting radius r can be modeled as a disk with radius r. This disk is being referred as an r-disk.

These r-strips are positioned such that the x and y co-ordinates of each node are given by:

$$x_{ij} = \left\{ \begin{array}{ll} \pm ir & \text{if } j \text{ is odd} \\ \pm\dfrac{(2i-1)r}{2} & \text{if } j \text{ is even} \end{array} \right.$$

$$y_{ij} = (j-1)\sqrt{15}r/2$$

,where i = 0, 1 ,2,…. and j refers to the r-strip number = 1, 2 ,3….

These r-strips are connected to each other by inserting some more sensors in the network, which will be referred as Global Connectivity Sensors (GCS). The positional co-ordinates of GCS are:

$$x_i = (-1)^i r/4$$
$$y_i = (2i+1)\sqrt{15}r/4$$

where i = 0, 1 ,2,….

Let us consider a portion of the network consisting of the sensors 1–6, as shown in Fig.6. The dots (●) represent deployed sensors nodes. The sensors 1 and 3 are located within two odd-numbered r-strips, whereas, the sensors 2 and 4 are within an even-numbered r-strip. The GCS (sensors 5 and 6) are positioned so as to connect the sensor 1 to 4 and 2 to 3 and hence, the corresponding r-strips are connected to each other. Such a placement of GCS allows an increase in the vertical spacing between the r-strips as compared to the network described by Kar and Banerjee [Kar, K., et al., (2003)]. This eliminates any overlapping between the r-strips (See Fig. 6) and hence, an increase in the coverage area as compared to [Kar, K., et al., (2003)], the details of which are presented in the next subsection.

4.3.4 Performance Evaluation and Comparison

As per the paper [Kar, K., et al., (2003)], nodes of adjacent r-strips are inter-connected with each other by inserting new nodes in between them (Node E & F in this case). Here node A & C lies on odd r-strips, while node B & D lies on even r-strips.

To ensure connectivity, maximum permissible distance between two deployed nodes (B & D) = r. Sensor E & F had to be so placed that their distance from A, B, C, D = r.

Since distance between node B and node D is equal to r, nodes E & F are placed parallel to nodes A & C. Fig 7. Therefore

$$BO = OD = r/2.$$

Now let's compute EO from right angled triangle BOE,

$$BE^2 = BO^2 + EO^2$$
$$r^2 = (r/2)^2 + EO^2$$
$$EO = \sqrt{(r^2 - r^2/4)} = \sqrt{3}r / 2$$

This gives,

$$AO = AE + EO$$
$$= r + \sqrt{3}r / 2$$
$$= 1.866r$$

which, basically is the vertical spacing between two r-strips as proposed by [Kar, K., et al., (2003)]. Similarly, compute AB from right angled triangle AOB,

$$AB = \sqrt{BO^2 + AO^2}$$
$$= \sqrt{(r/2)^2 + (r + (\sqrt{3}/2)r)^2}$$
$$= 1.931\ r < 2r.$$

Hence there is overlapping between r-disks lying on alternate r-strips. This is the limitation of previous work. In order to overcome this limitation, we propose to increase vertical spacing so as to reduce overlapping. This can be done by inserting the interconnecting nodes E & F at points as specified in Fig. 8. With such placement, we would have

$$BO = OD = r/2$$

and

$$AB = 2r$$

Now let's compute the vertical distance (AO) between alternate r-strips,

$$AO = \sqrt{AB^2 - BO^2}$$
$$= \sqrt{(2r)^2 - r^2/4}$$
$$= \sqrt{15}/2\ r = 1.936\ r$$

The value of AO reflects that our algorithm has been able to increase the vertical spacing between two r-strips which in turn would lead to reduced overlapping and also the number of sensors to be deployed. It implies that overall time of deployment of sensors, the cost of deployment and the cost of sensors is significantly reduced. The result clearly indicates that our algorithm and placement pattern provides connected coverage to entire field.

5. Conclusions and Future Work

The work presented in this paper makes a unique contribution towards the deployment of wireless sensors in subsurface as at the time of listing, none other researchers have proposed any mechanism to deploy sensors in subsurface and also the proposed strategy of deployment is efficient as compared to other existing strategies in other related fields. The work only focused on the deployment of sensors ignoring the communication strategy or routing protocols to be employed. A routing protocol that can adapt to the prevailing conditions, node failure and data loses shall be taken over as future work.

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Table 1. Phases and their Key Functionalities

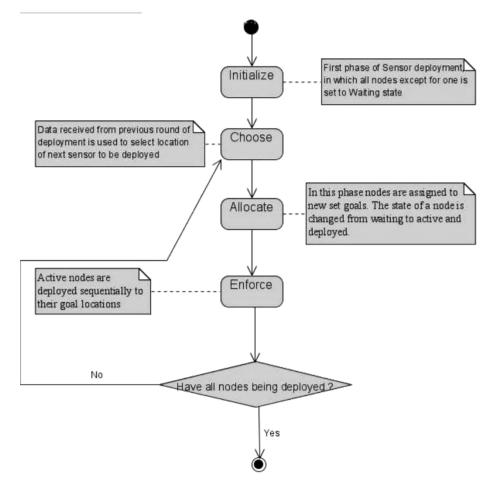| Phases	Key functionality
Initialize	Set the state of a node to *waiting*, *active* or *deployed*.
Choose	Develop a location map with the help of deployed nodes and select the appropriate location for waiting node.
Allocate	Assign destination to a waiting node and set the state as active.
Enforce	Active node is deployed at the desired location successively

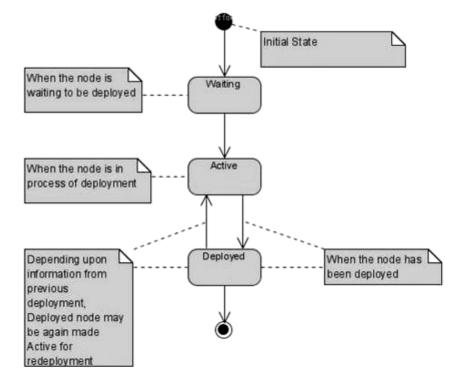Figure 1. Transition between various phases of the algorithm
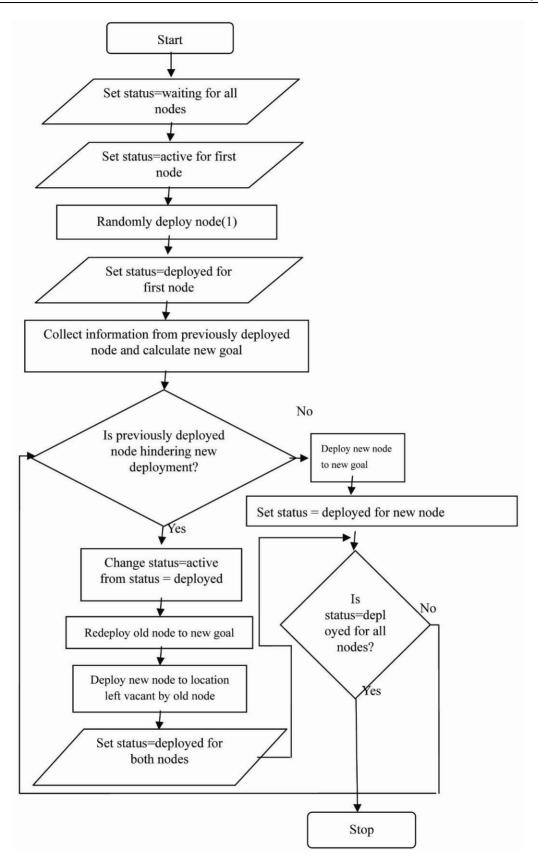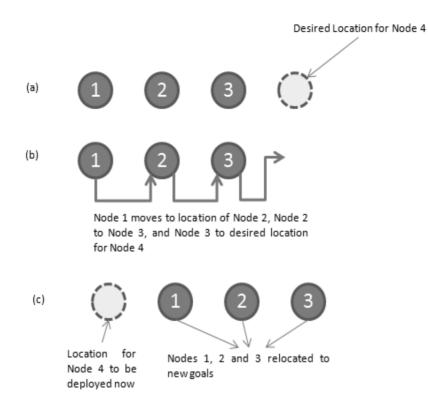
Figure 2. State Diagram of nodes being deployed

Figure 3. Flowchart
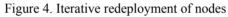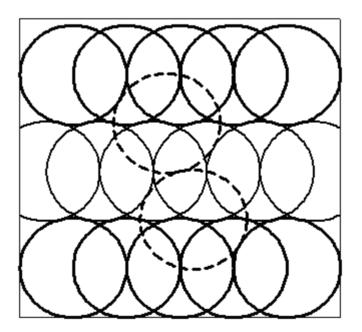
Figure 4. Iterative redeployment of nodes
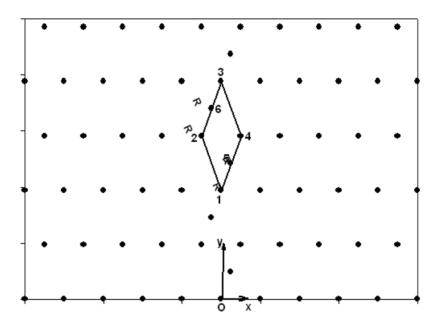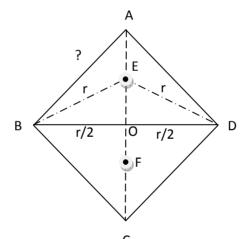

Figure 5. A 2D Allocation Grid

Figure 6. Connectivity and Coverage Description

Figure 7. Detailed view of r-strips placement as per [Kar, K., et al., (2003)]
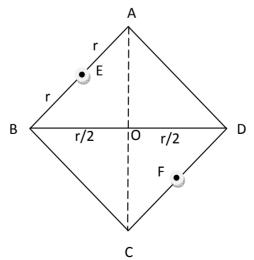

Figure 8. Detailed view of r-strips placement as per our proposed model