Enhancing the Coverage of 3D Wireless Sensor Networks Based on Monte Carlo and Grid Quadrature

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Abstract – Wireless sensor networks is a fast emerging area for research and commercial growth. Sensor networks are very useful for military, environmental, and scientific use to list a few[1] . Despite of the numerous applications they have; sensor networks comes with a number of perplexing problems for example location, deployment, and tracking [2]. One of the perplexing problems in sensor networks is the coverage problem, which mirrors how well a sensor network is observed or traced by sensors. In this manuscript, new coverage model in 3D environment using Monte Carlo (MC) and, grid quadrature are presented in detail aiming to carry out the estimations of the coverage ratio which is the core case. Also, an improvement of coverage improvement technique centered on virtual force algorithm is introduced which address coverage problem especially when there are narrow number of sensors. Simulations result indicated that, all our methods converge to the right solution; Coverage is vividly improved, and the computation complexity for both the coverage ratio estimation and the coverage enhancement are significantly reduced.

Index Terms - Wireless Sensor Networks, Wireless sensor, Coverage Ratio, Coverage Enhancement, Monte-Carlo, Virtual Force, sensor nodes, technique, method, Coverage area, region of interest, algorithm, simulation

1. INTRODUCTION

Coverage in wireless sensor networks (WSN) is one among the research issues that have been in discussions for years. Although some contributions have been made in this area but there still exists number of encounters to be solved. The uses of wireless sensor network have been increasing thus making it so important to discuss how we can use the limited number of sensors to cover more locations subject on the purpose. One among the most essential concepts when addressing the matter of coverage in wireless sensor networks is the calculation of coverage ratio [2]. Also there is a widely used assumption that sensors have uniform sensing ability. Along with other topics under hot discussion in wireless sensor networks such as location calculation, tracking, and deployment, is the coverage issue [3]. However many research works which have been done to resolve the coverage problems in wireless sensor network rest on a 2D scenario. There are few contributions that have already been presented to resolve the coverage problem matters in a 3D scenario. However in real life and in the future we expect to have more uses of wireless sensor network in a 3D environment thus there are demands for more study in this area [4].

Coverage in wireless sensor networks pronounces how best a sensor network will monitor a field of interest. It can also explain a measure of quality of service. Coverage can also describes how the field area can be monitored by the given number of sensors both in spatial and temporal view [5]. Spatial coverage requires the entire region of interest to be covered in one or other time whereas temporal coverage requires all points to be covered all the time. Depending on the particular application a detailed study is always performed on the targeted area to know how many sensor devices are essential to cover that area. However it is significant to ruminate some other parameters like cost and power consumption thus it is vital to assure that the finest solution can be provided using small number of sensor nodes while attaining the anticipated result at the same time [6].

It is essential to mend coverage due to the following reasons reasons; when we mend coverage it is easier to get genuine information as soon as possible, for example we can easily detect some marine intruders when wireless sensor network coverage is enhanced. We can also improve cost and save time since we don't have to go physically to monitor the location. Power consumption can also be enhanced when we have advanced technologies which can enhance coverage but yet use least possible number of sensors [7].

In this study, we present the matter of using k-d tree data structure such that, we minimize the computation complexity of both the coverage ratio estimation and the coverage improvement. This adjustment makes both of our proposed techniques to be more practical in the real life uses of wireless sensor networks. And we will also address coverage problem especially when there are narrow number of sensors [8].

1.1 Current Situation of Wireless Sensor Networks

As admitted earlier, there are numerous research works which have been done already in coverage of wireless sensor network making it among the hot topics under discussion although most of such researches are based on 2D scenario. Although the purpose is to raise the uses of wireless sensor network and making life simple but we cannot clash the mere fact that, some of the uses are anticipated to be done in a 3D scenario. For example the similar technique used in monitoring situations in the land surface cannot be utilized exactly the same way as techniques used to monitor situations in the water bodies since these are two different environments.

Some examples of efforts which have been taken to improve coverage matters in wireless sensor network include research works such as designing of Localized Algorithms for Barrier Coverage in which is grounded on the observation that, movements are anticipated to tail a shorter path in crossing a belt region, local barrier coverage ensures the tracking and detection of all movements such that their path are confined to a slice of the belt area of deployment [6]. It was shown that, it is likely for individual wireless sensor nodes to locally determine the existence of local barrier coverage, even in conditions where the location of deployment is anticipated to be arbitrarily curved [9]. Another example of research work to improve coverage is that addressing coverage problem in Wireless Ad-hoc Sensor Networks in which the focus was combining some computational geometry and some graph theoretic methods for instance the Voronoi diagram and graph search algorithms. Comprehensive experimental results were also presented [6].

However one among the real facts about the research situation on coverage issue is that; still there are very few research works which have been done already to address the issue of coverage in 3D environment and thus there is still a room for more researches in this area, this is due to the mere fact that, the uses of wireless sensor networks in this environment keeps increasing daily.

In this research, we used a famous method called Monte Carlo method which was already introduced in 2D environment but we will improve the technique and then use the idea to solve coverage challenges in 3D environment.

1.2**.** Our contribution and organization of this paper

In this study, we present new coverage model in 3D environment. Techniques called Monte Carlo (MC) and grid quadrature are presented in detail aiming to carry out the estimations of the coverage ratio which is the main case. This paper presents a novel improvement on the Monte Carlo method based on the k-d tree structure named MCKD-CRE (Monte Carlo K-Dimensional Coverage Ratio Estimation).

Also, the application of virtue force in enhancing coverage will be presented in this paper. Our approach is utilized in a sensor node network with a sink or a center server. The sink node knows all the location of all other sensor nodes; it calculates the final position of other sensor nodes, and commands all other nodes to move directly to the final position. Specifically, a virtual force method based on range query capacity of the k-d tree will be introduced.

The remaining part of this manuscript is structured as follows: Section two (2) describes related works done by other researchers; Section three (3) describes the proposed modelling aiming to enhance coverage in 3D Wireless Sensor Networks. In Section four (4) simulation results are analyzed and discussed. Section five (5) gives conclusion about this paper by summarizing the authors' views on how the proposed modelling has improved the coverage in 3D Wireless Sensor Networks.

2. RELATED WORK

With the improvement of technology, the uses of wireless sensor networks has been increasing at a very fast rate such that, many aspects of our lives depend on their applications. There are so many fields where wireless sensor networks have wide range applications and the following are just some examples: acoustic detection, environmental/habitat monitoring, military surveillance, medical monitoring, inventory tracking, smart spaces, seismic detection and, process monitoring [10].

In this part, we make a perusal on existing research concerning coverage in wireless sensor network [11]. We shall discuss topics such as coverage problem and coverage techniques in wireless sensor network [12]. The issue of coverage ratio and enhancement in wireless sensor network, sensor nodes deployment strategies in 3d, virtual forces and energy issues in wireless sensor network [13].

2.1. Coverage-related Index

The subject of coverage in wireless sensor network rest on a number of aspects like topology of the network, sensing mode of sensors and most significantly is deployment. This approach permits us to locate the sensor nodes in our field of interest which refers to the favorite field of coverage. Essential dynamics to consider when utilizing wireless sensor networks includes; coverage and connectivity. Wireless sensor networks need to meet both of these requirements i.e. coverage and connectivity [14].

2.2. Coverage

Individual sensor device has physical sensing range in which it can perform its operation. One objective of a sensor network is that, each location in the physical space of interest should lie inside the sensing range of one or more sensor nodes.

The coverage ratio is a terminology used to signify the ratio of the area covered by sensor and the entire area [15]. It is one among the standards used to measure the performance of wireless sensor network, and it enlightens a ratio between the number of data points whose probability of detection surpasses the threshold; and the total number of data points in the area under surveillance. Preservation of coverage, assessment of unique ID and extension of network lifetime are vital features for wireless sensor networks. Classifying sensor nodes into clusters is considered to be an effective way to enhance the performance of the network [16]. The ratio of covered area to area under interest and the network life span are two of the most challenging matters in wireless sensor network and are known as coverage ratio problem. The coverage ratio generally explains how well the area of interest is monitored by the sensors nodes. Performing derivation of coverage ratio from target area remains to be one among the crucial issues when dealing with wireless sensor network.

Monte Carlo method is a simple and elastic method for approximation of solutions in physical science and engineering [17], and is also possibly used to approximate the coverage ratio of wireless sensor network. Using the Monte Carlo method, it is easy to resolve the problems through the simulation of the sample data. However, using Monte Carlo technique necessitates a large amount of computation to attain accurate result because this method requires many sample data. In wireless sensor network, Monte Carlo method can be used to perform operations such as Calculations of coverage and Estimations of localization. In a Monte-Carlo technique, the essential answer is expressed as a quantity in a stochastic model and approximated by random sampling of such model.

Monte Carlo is among the most useful and widely used numerical techniques. Its convergence rate, $O(1/(N)^{1/2})$, is autonomous of dimension, which displays Monte Carlo to be very robust although is slow.

2.3. Area Coverage

The main objective of wireless sensor network is considered to be covering (monitoring) the area of interest. We consider that each point in the region of interest is essential to be monitored since full coverage is a necessity for valid data otherwise coverage holes may exist [18]. The kind of coverage of a whole area is branded as full or blanket coverage and in this kind we make sure that each single point inside the field of interest lies within the sensing range of at least one sensor node. Ideally, it would be significant to set up the least number of sensor nodes inside a field in order to achieve blanket coverage [19]. In full coverage we consider assigning the nodes in a concept known as an r-strip such that each individual sensor is positioned r distance away from the neighboring sensor, where r denotes radius of the sensing area. The strips can then be arranged in an overlapping layout such that blanket coverage is attained. The biggest challenge in this solution is the fact that, it is not practical in deploying sensors in such formats [2].

2.4. Point Coverage

The core purpose of point coverage is covering the targets having known location needing to be monitored. Structures in point coverage focus on determining exact positions of sensor nodes [20]. Point coverage is considered to be a special type of coverage. It is known that in area coverage some points stay undetected because of some problems hence in such situations point coverage may be implemented [21]. Moreover, in some applications, when having a sufficiently dense network, area coverage can be estimated through a guarantee of point coverage in which case the entire points of wireless devices can be deployed to embody the whole area, and the functioning sensors are likely to cover all the sensors and monitor the target.

Target coverage denotes observing a static number of targets. In target coverage problem, we have to consider finding an optimal scheduling for sensors in such a way that, the time (called lifetime) to track every target can be longest possible. Unluckily, the target coverage problem has been shown by researchers to be Neyman Pearson complete (NP-complete). One among major issues in Target-coverage challenge in wireless sensor network is increasing the network life span. This can possibly be resolved by considering least working nodes to cover all the targets [22][10] and all targeted areas are covered by at least one sensor node. In most situations, sensor nodes are tightly installed to tolerate failures. It is irrelevant to turn on all sensors in the region of interest aiming to cover all the targets; this is because more than one sensor can cover the same target. Thus, it is essential to divide the *n* sensors into some subgroups, and each subgroup can cover all our targets of interest. In every time slot, only one subgroup is active. The task of monitoring targets is cycled in the entire wireless sensor network. The core purpose of performing duty-cycling is to save energy and rising the life span of the wireless sensor network [23].

A model called discrete target model was proposed in [24] to resolve the coverage breach problem. In this approach the source of observation is given to be a set of fixed points. Each point source is considered to have has detection range. Suppose it possess equal probability of performing object detection from different directions, such that such objects have equal probabilities of being detected from all directions, it follows that the circular area can represent the detection range. It is significant to note that, different source activities can possess different detection area so long as some sensor nodes are located within the boundary of that particular area and therefore the point source is known to be covered. In general, the monitored source can be a specified location or an event that can occur at any point in the region. From the mere fact that, there is no pre-specified fixed point source is provided. A simple way to solve this type of problem is to change the area coverage problem into a fixed point coverage problem by performing the division of the monitored area *A* into a set of fields, and then consider the fields as discrete point sources [24].

In previous research works the breach problem in wireless sensor network showed to be caused by the limitation of the communication bandwidth and it was discussed in details. Minimum breach Problem was clearly elaborated and it was proved to be NP-complete [25]. A model called 0-1 integer programming model was developed, algorithms denoted as two polynomial time approximation algorithms were introduced and debated. In depth simulation was also conducted to compare the performance of the two proposed algorithm and conclusions obtained from such simulations were shown to be consistent with the prediction. Bandwidth constraint was shown to be a real limiting factor when addressing the problem of sensor network coverage. It was also noted that as items move from place to place, the sensors deployed on the wall should be able to detect them. This requires that, we should keep tracking the items continuously or with bounded intervals of breach. The proposed methodology helped to address these problems and it was stated that, such a methodology must be complemented by increasing bandwidth or else there would be minimization coverage.

2.5. Path Coverage

Path coverage is known to be one among the monitoring examples which is employed to sense a particular specific path and report possible wireless sensor network efforts that have already been made by intruders to cross it. Exploration shows that, in a manual network deployment, the essential level of the path coverage can be attained through proper deployment of the sensors over the area [26]. When it is impossible to perform network deployment manually, random deployment is a better option [27]. An example can be dropping sensors from an aircraft. Regarding the randomness of the sensors location, network coverage articulates a stochastic trait and the expected full path coverage is not a guarantee [28].

Barrier coverage is another kind of coverage which is very critical in wireless sensor network for security uses with the objective of detecting intruders attempting to penetrate protected locations. But it is significant to note that, it becomes hard to achieve desired barrier coverage after first random deployment of sensors since their locations cannot be controlled or predicted [29]. However, although the technique promises to bring a lot of advantages, it is also associated with some challenges; the first challenge is that, barrier may not be generated after initial installation of sensor networks. Also, due to some issues like budget limit and, and due to a mere fact that lots of ROIs (Regions Of Interest) are difficult and dangerous to reach, a substitution technique of random employment of sensors (e.g., dropped by aircraft) is widely used which in turn makes the locations of sensor nodes random and unpredictable. It is therefore not easy to form a barrier after initial employment of sensor networks [9]. The other challenge is that, in order to achieve the application requirements, different kinds of sensors are installed to create a barrier to detect intruders. It is important to note that different kinds of sensors have different parameters like communication, costs and computation capabilities. Because of the limit of the budget it is not easy to apply all the types of sensors we would wish to use. Design deployment method is such a challenging matter in order to attain application requirements of this kind of coverage by using different types of sensors within the available budget limit.

Barrier coverage is also largely affected by the location errors of sensors [9]. We stated earlier sensor nodes are normally randomly deployed in the ROI thus making the true locations of sensors difficult to predict. It is so costly to equip GPS receivers on each sensor because of large-scale sensor networks. Regarding solving this problem of costs, the solution is to equip GPS receivers on a small portion of sensors beacons and then estimating the location of the remaining sensors using the beacons' location information.

2.6. Coverage Enhancement with Deployment or Redeployment

Grid placement is a common method to locate sensor nodes in the region. The supervised region has been deployed with the position of wireless sensor nodes which are known. The nodes possessing the property of mobility then gets included into the monitor environment. The real challenge here lies in where to locate the mobile nodes. In order to provide perfect destination for those sensor nodes, a grid based methodology is planned in this work. The atmosphere is partitioned into a number of grids [30]. The center of charge in this work is considered to be known. Square shaped grids having same edge is taken into account along with the advantage of grid sizing which is adaptive inherently. The benefit in having smaller sized grids is that, they can yield good declaration in terms of resolution.

Similarly, the advantage in larger grids is that, they can minimize the difficulty in computation. The proposed technique would perform the valuation of weight for every single grid [31] and after that it is essential for the next step to find out minimal region, which has been done. The key aspects such as area coverage as well as system stability can be enhanced by means of locomotion of mobile nodes. However, deterministic deployment approach [32] is neither practical nor feasible; thus another method is suggested in which employment option is to cover the sensor field with sensors randomly distributed in the region of interest. The stochastic random distribution method can be of different kinds such as uniform, Gaussian, Poisson or any other distribution subject on the application [11]. An assumption of uniform sensor distribution was made although the approach could be applied in any other deployment scheme consisting of the sensor nodes. Some concepts like Worst Case Coverage Maximal Breach Path, Best Case Coverage-Maximal Support Path and Complexity issue were also presented [33].

2.7. Coverage Enhancement with mobile nodes

One among the effective approach to improve coverage is by making use of mobile sensor nodes. In this way we can cover a large area using least number of sensors. In this part, we discuss some techniques used to improve coverage by mobile sensor nodes. One among the technique is called energy efficient self-organized distributed greedy heuristics technique which is suggested to maximize area coverage in such a way that the amount of computation and circles of communication, and the distance navigated by a node, can be minimized utilizing small number of nodes[23].

It is obvious that, whether the node employed be deterministic or random, there is slight scope of enhancing the coverage when the nodes are spatially distributed and they stay static [8]. Thus, mobility-assisted node employment for efficient coverage has emerged as a more challenging issue. Many methods have been suggested so far, based on swarm intelligence, virtual force, and computational geometry, or some combination of the above methods [6]. Based on Voronoi diagram, some researchers designed and evaluated three (3) distributed self-deployment algorithms for governing the movement of sensors to attain coverage [34]. A movement-assisted node placement method is suggested based on Van Der Waal's force. However, the computation involved is complex and it takes great number of iterations to converge and also, the displacement of nodes may be large.

Some authors have suggested a distributed algorithm for independent employment of mobile sensors, where sensors direct their movements in order to attain a complete and constant coverage. Regarding the same problem, some tessellated the area into hexagons and placed the nodes in each apex and center of the hexagons to guarantee the area coverage.

For dissimilar sensor nodes in wireless sensor networks, a novel deployment algorithm based on the circle packing technique has also been presented where beginning from the first random employment, the coverage area is enhanced iteratively to assure the absence of coverage hole and obstacle avoidance [35].

2.8. Coverage Enhancement with node selection or scheduling

Some researchers concentrated on cluster head selection problem to enhance whole network coverage and analyzed how the perimeter coverage technique can be used by periodic assortment of cluster head nodes in dissimilar wireless sensor network to guarantee the coverage [36]. The challenge of stochastic coverage in dissimilar sensor networks has been addressed and also considered this problem as a set crossing problem. Researchers derived systematic formulae enumerating the coverage attained by stochastic employment of sensors on a planar field of interest. However, these methods are in general computational intensive.

A light-weight distributed greedy heuristic to exploit area coverage in such a way that the amount of computation, circles of communication, and the distance traversed by a node, can be minimized utilizing least number of nodes which can be a better alternative. A Multi-Objective Immune Algorithm (MIA) conquers the coverage holes and maximizes the coverage and rearranges mobile sensors dependent on restraining their mobility with regards to their range aiming to conserve the connections in network [35]. The main steps of MIA are population generation in which pool of position antibodies (PA) are generated and objective function evaluated. MIA works on two principles first to exploit the coverage area and second to limit the mobility cost by preserving connection among nodes. Given an existing distribution of sensors, it is frequently necessary to diminish the number of sensors that remain active while still achieving complete coverage of the entire region. If all the sensors are active simultaneously, an extreme amount of energy would be wasted due to packet collisions. Further, the data collected will also be extremely associated and redundant. Thus there is a demand of some techniques wherein the sensors make local decisions on whether to sleep, or join the set of active sensors. If the sensing area of a sensor is entirely covered by its neighbors, then the sensor can be disabled without affecting the whole coverage [20].

For lively coverage, many authors showed energy efficient sleep scheduling algorithms to guarantee the coverage, where sensor nodes sporadically go into sleep mode, and hence conserve energy [10]. Virtual segregating has been utilized to decompose the query area into square grid blocks and the coverage issue of each block is examined.

2.9. Coverage Enhancement by node cooperation

Another strategy which was introduced aiming to perform 3D space detection and improve coverage of wireless sensor network was the use spatial correlation [37]. This technique was applied among the measurements of sensor nodes to conduct the research of the signal detection and sensing space coverage issues of wireless sensor network in 3D region. We observed that the wireless sensor technique can be utilized to gather and process signals from the source incident in the space.

The binary detection model was also used to establish whether the event in a particular spot occurred or not [38]. However this assumption is not practical. The intensity of the signal from the event was shown to decrease as the distance from the sensor node increases in actual situation while the signal is disturbed by the noise in that location.

These issues make the sensor node difficult to precisely detect the appearance of the event in the 3D space because of the "false alarm" or "missing alarm". In actual sense, we tried to address two problems: The first problem was which detector should be applied on the nodes aiming to make their sensing range wider and another problem was establishing the finest way to install the nodes aiming to obtain seamless coverage for a 3D space in such a way that the number of nodes is reduced.

In this case the first focus was to detect issues by making use of probabilistic sensing model associated with five distinct detectors [18], this relies on spatial correlation and theory of signal detection. Considering that spatial correlation can improve the detection performance of detectors, different sorts of cooperative detectors with spatial correlation was selected aiming to obtain the appearance of the target event and such detectors are like collaborative mean detector (MD), collaborative energy detector (ED), collaborative covariance detector (CD) and collaborative enhanced covariance detector (ECD).

Along with the principle of Neyman–Pearson (N–P principle) [24], each of such detectors was applied on wireless sensor nodes to identify the incidence of an event giving rise to different probabilities of detection. Then the probability sphere of every detector can be found by the famous Monte-Carlo method, and its surface is made of the sampling points with similar probability of detection, this sphere is called unit sensing model and its associated radius is called sensing range of sensor nodes [6].

3. PORPOSED MODELLING

3.1. Coverage Ratio Estimation

Coverage ratio is a very important parameter when dealing with the subject of coverage improvement in wireless sensor network. In our scenario coverage ratio can be explained as the ratio of whole volume to the volume covered by the sensors in a given 3D space.

In this study, we only concentrate on the area coverage and then define the coverage ratio at first. Also we will introduce Monte Carlo (MC) method and grid quadrature method to estimate the coverage ratio. Since Monte Carlo method is slow, and grid quadrature is not practical, we will present a novel improvement on the Monte Carlo method based on the k-d tree structure.

3.2. System Model

Given that, different coverage objects are with different coverage quality standard. In this study, we only focus on the area coverage.

Assume that there are N sensors employed in the region R in 3D space. The sensor nodes are listed as $\{S_1, S_2, S_3, ...S_N\}$.The position of sensor node S_i is denoted by the symbol S_i itself and also its x-y-z coordinators (x_i, y_i, z_i).We define the range of the sensor node S_i is a constant number L_i.It means the sub-region B_i that S_i can sense is given by

$$B_i = \{p \mid p \in R \wedge \|p - s_i\| \le L_i\} \quad (1)$$

Equivalently,

$$B_i = \{(x,y,z) \mid (x,y,z) \in R \wedge \|(x,y,z) - (x_i, y_i, z_i)\| \le L_i\} \quad (2)$$

Here the symbol || (x,y,z) || denotes the norm in the Euclidean space given by

$$\|(x,y,z)\| = \sqrt{x^2 + y^2 + z^2} \quad (3)$$

The volume of R is denoted by $|R|$ and the volume of B_i is denoted by $|B_i|$.Note that B_i is a sphere in 3-D space, we have:

$$|B_i| = \frac{4}{3}\pi L_i^{\,3} \quad (4)$$

A typical network deployed in 3-D space is shown in Figure 1. A total of 10 nodes are deployed. The green balls are the sensing sub-region of sensors. All the sensors are located in the center of the balls.

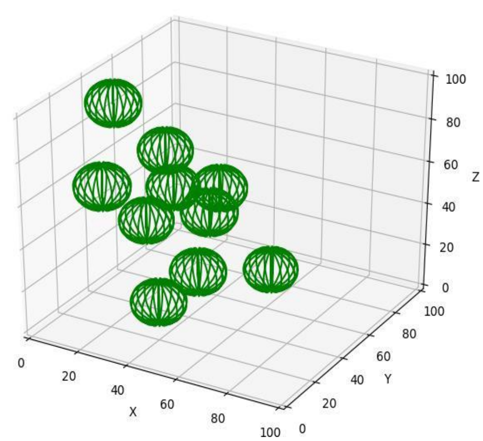


Figure 1 3D sensor node deployment

With many sensor nodes employed in the region R, if a point p is covered by any sensor nodes, i.e. any of the distances from p to all sensor nodes is less than L, we ca say that p is covered by the sensor network. All the points which are covered by the sensor network are called the covered region B .Thus, B is the union set of the entire sub region $B_1, B_2, B_3, \ldots, B_N$.

$$B = B_1 \cup B_2 ... \cup B_N = \bigcup_{i=1}^{N} B_i \tag{5}$$

We define the coverage ratio C is the ratio of the volume of B to that of the whole region R:

$$C = \frac{|B|}{|R|} = \frac{|B_1 \cup B_2 ... \cup B_N|}{|R|} = \frac{\left|\bigcup_{i=1}^{N} B_i\right|}{R} \tag{6}$$

Since B is the union set of all $B_1, B_2, B_3, \ldots, B_N$, there are possible overlapped region among the sub-region of sensor nodes, which make it difficult to calculate the volume of the covered region B.

3.3. Grid Quadrature and Monte Carlo Methods

Since the estimation of the coverage is a difficult problem, especially for the case where the sensing radius $L_1, L_2, ..., L_N$ are not identical; then there are some methods to deal with such a problem. Some of these methods are efficient in some environment and conditions and others are efficient in other different scenarios. After an intensive review of some of the various coverage methods proposed, we will focus on Monte Carlo (MC) method and regular sampling method.

Monte Carlo method is a well-known technique which has been adopted in different research environment nevertheless this will be the first time we use this method to calculate the coverage ratio and estimate the volume in 3D environment. This will result in the fulfillment of our core objective which is to enhance coverage in 3D space.

3.4. Monte Carlo deployment method

Monte Carlo method can be described as a technique that is used to perform statistical evaluation of some mathematical functions by making use of random samples. Like many other algorithms, there are also some errors associated with Monte Carlo method but these errors can be minimized by using more number of random samples and consequently get more accurate output. Monte Carlo method is an easy and flexible method to approximate different solutions in physical science and engineering fields.

We can also define a Monte Carlo technique as a generic numerical method that uses computer and making use of pseudo-random numbers to perform simulation of stochastic inputs in order to perform creation and processing of large numbers with possible outcomes. Monte Carlo method solves problems through generation of reliable random. Monte Carlo technique is commonly used for generating simulations in many fields which require solutions for problems that not practical or which are impossible to solve by using traditional analytical or numerical methods. It is essential to note that Monte Carlo simulation is basically applied when we want to predict the final effects of a series of occurrences such that each has its own probability.

A big requirement when deploying Monte Carlo method is that, the mathematical system should be described by probability density functions. If the density functions are obtainable, then the Monte Carlo simulation can proceed by making use of random sampling from such density functions and apply them within the simulation.

Since, we used Monte Carlo method we have to find the definite integral of a function by selecting a large number of independent-variable samples randomly from within an interval or region, then we find the average of the resulting dependent-variable values, and finally we divide by the span of the interval or the size of the region in which the random samples were selected. This varies from the definite integral approximation in which samples of independent variables are selected at equally-spaced points inside an interval or region.

Mathematically, our objective is to calculate the volume of B .Thus we want to obtain

$$|B| = \int_B 1 \cdot ds \tag{7}$$

By defining the indicator function of a set X as

$$\mathrm{I}_X(p) = \begin{cases} 1, & \text{if } p \in X, \\ 0, & \text{else.} \end{cases} \tag{8}$$

Thus Eq. 8 leads to

$$|B| = \int_B 1 \cdot ds = \int_R \mathrm{I}_B(s) \cdot ds \tag{9}$$

$$C = \frac{1}{|R|} \int_R \mathrm{I}_B(s) \cdot ds \tag{10}$$

This offers a way to estimate the coverage ratio C. We first generate M random variable uniformly

$\{w_1, w_2, \ldots, w_i, \ldots, w_M\}$ distributed in R, and then approximate the result by

$$C \approx \frac{1}{M}\sum_{i=1}^{M} I_B(w_i) \tag{11}$$

The following are some of the general main steps to consider when making use of Monte Carlo Simulation:-

Perform modeling of the inputs and process; Draw a vector to represent random varieties; Perform evaluation of the function of interest; Perform once again the second and third steps for many more times thus aggregating the results.

In order to understand how we could use Monte Carlo method to estimate the volume of the union of spheres (which is an assumption made for the underwater 3D environment), we will perform the following steps. [Here we assumed all sensing radius L_i are equal to a constant L .]

Algorithm 3-1 Monte Carlo Based Coverage Ratio Estimation

Require: $B_1, B_2, B_3, \ldots, B_N$, R, L

Ensure: C

Generate random variables uniformly $\{w_1, w_2, \ldots, w_i, \ldots, w_M\}$ distributed in R .

Count:=0

For k **in** [1, M] **do**:

Sensored := False

For j in [1, N] do:

Calculate distance d:= $\|w_k - s_j\|$

If $d \le L$:

Sensored :=True

Break

End if

End For

If Sensored:

Count := Count+1

End If

End For

C:=Count/M

It should be noted that the time computation complexity of MC-CRE is O(MN) in an average manner. The convergence rate is $O(M^{-1/2})$. It means that, with 100 times more number of the sample points, the accuracy of MC-CRE is only improved 10 times.

The figure 2 below illustrates the sequence of calculations needed to apply Monte Carlo techniques to approximate the volume of sphere in the region R.

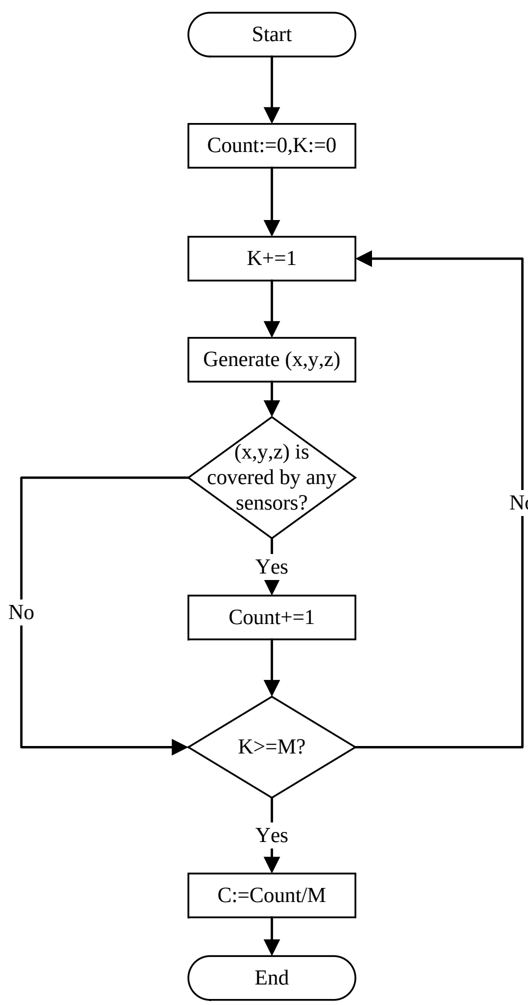


Figure 2 MC-CRE Flow Chart.

3.5. Grid Quadrature method

Sometimes random arrangement of sample points could cause the convergence rate estimates the coverage ratio in the sensing region so in this case it is a good idea to perform grid sample points. We call this method as grid quadrature.

With the same assumption, to adopt the Grid Quadrature based Coverage Ratio Estimation (GQ-CRE), we first generate M sample points which lie in a regular grid $\{w_1, w_2, \ldots, w_i, \ldots, w_M\}$ inside R , and then approximate the result by

$$C \approx \frac{1}{M}\sum_{i=1}^{M} I_B(w_i) \tag{12}$$

A simple grid is the stack of regular cubes. We assume that R is a regular cube with its height, width and, depth all equal to a.We divide a into m segments, where $M = m^3$.We set the sample points at the center of each small cube of which the height, width and, depth are a/m , as shown in Figure 3.

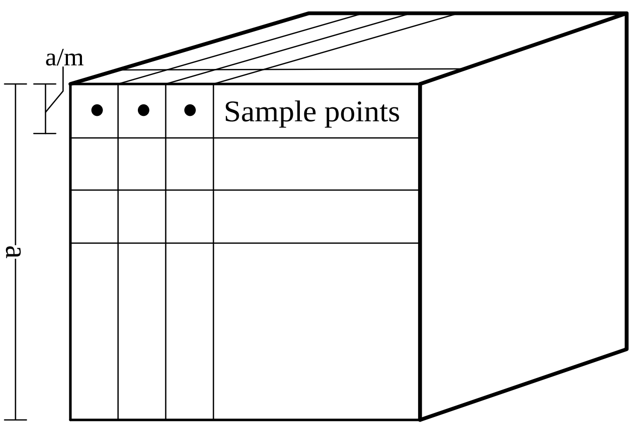


Figure 3 Sample points for grid quadrature

The network coverage ratio describes a ratio between numbers of data points whose detection probability surpasses the threshold to the total number of data points in the given location under surveillance. It should also be noted that the time computation complexity of GQ-CRE is O(MN) in an average manner. However the convergence rate of GQ-CRE is possible and faster than that of MC-CRE. It means with 100 times more number of the sample points, the accuracy of GQ-CRE is possibly improved more than 10 times, however, the GQ-CRE is not practical in the real applications. This is because; first, we can only select the M value from a limited set in the integer numbers. For the above-mentioned cases, M must be a cube of an integer m.When m doubles, M will be eight times bigger. Thus it will lead to lots of computation cost. Second, the result of GQ-CRE depends on the deployment of sensor nodes. If sensor nodes are also deployed in the regular manner, it will possibly cause huge mistakes based the relation of the grid deployment and the grid sampling points. Therefore, we will mainly focus on the improvement of the Monte Carlo methods in the following sections.

3.6. Monte-Carlo Coverage Ratio Estimation with k-d tree

We have stated that Monte Carlo method is slow, and grid quadrature is not practical. Thus in this paper, we will design a novel improvement on the Monte Carlo method based on the k-d tree structure, named MCKD-CRE.

In computer science, a k-d tree, i.e. k-dimensional tree, is a space-partitioning data structure for organizing points in a k-dimensional space. K-d trees are proved to be a useful data structure for lots of applications, such as searches involving a multidimensional search key. Especially, k-d tree offers range searches and nearest neighbor searches like; time complexity notations of search, insert, and delete operations in k-d tree all are $O(\log n)$.

With the support of k-d tree, the MCKD-CREs are listed as below.

Algorithm 3-2 Monte Carlo Based Coverage Ratio Estimation with k-d tree

Require: $B_1, B_2, B_3, \ldots, B_N$, R, L

Ensure: C

Generate random variables uniformly $\{w_1, w_2, \ldots, w_i, \ldots, w_M\}$ distributed in R

Generate k-d tree T with the point set $\{s_1, s_2, s_3, \ldots S_N\}$

Count:=0

For k **in** [1, M] **do**:

Query T for the nearest neighbor of w_k

Calculate nearest neighbor distance d

If $d \le L$:

Count := Count+1

End If

End For

C:=Count/M

The time computation complexity to build a k-d tree in the beginning of MCKD-CRE is O(NlogN) in an average manner. In each iteration, the nearest neighbor query is O(MlogN).Thus the total time computation complexity if MCKD-CRE is $O(N\log N + M\log N)$, which is significantly less than that of MC-CRE. Note the convergence rate is still $O(M^{-1/2})$. But we can do more simulation in the same time span.

3.7. Applications and impacts of virtual forces method on our proposed model

Coverage Enhancement:

In this part, we present a coverage enhancement method in the sensor network with a sink or a center server, design a centralized Virtual Force Method based on efficient range query capacity of the k-d tree. In our algorithm, the coverage ratio is monitored on each step of iteration so as to exit the procedure if the coverage ratio is above the threshold ratio. Only the neighbor nodes in the distance of twice the sensing radius are used to calculate the virtual force and these forces are always try to push near nodes apart. Finally, the algorithm is verified by simulation.

From the existing Virtual Force Model:

Suppose s_i denote any sensor node and (x_i, y_i, z_i) denotes its corresponding coordinates. At every step of iteration each node broadcasts a Hello message with its location. Also the nodes hear so as to perform the neighborhood discovery. Once the node knows its 1-hop and 2-hop neighbors, it calculates its new location according to the forces exerted on it by those neighbors.

Let d_{ij} denote the Euclidean, then the distance between the sensor nodes s_i and s_j. d_{ij} is given by

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \tag{13}$$

The force exerted by sensor s_j on sensor s_i is given in [39] by:

$$F_{ij} = K_a \cdot (di_j - D^{th}) \frac{(x_i - x_j, y_i - y_j, z_i - z_j)}{d_{ij}} \tag{14}$$

A repulsive force, if $d_{ij} < D^{th}$

$$F_{ij} = K_a \cdot (D^{th} - d_{ij}) \frac{(x_i - x_j, y_i - y_j, z_i - z_j)}{d_{ij}} \tag{15}$$

Otherwise, the force is null. The total force F on s_i is the sum of these forces exerted by its 1-hop and 2-hop neighbors. Then the node moves according to the total force. Here the virtual forces are limited in 2-hops, but is not the most limitation.

The Improved Virtual Force Method based on k-d tree:

We consider such a sensor node network with a sink (or a center server). The sink node knows all the location of all other sensor nodes. It calculates the final new position of other sensor nodes, and broadcast the result to all the other nodes. Then, other nodes directly move to the final position which is carried in the packet from the sink.

We also use similar Virtual Force Method, but we notice that the method is slow if all the nodes push or pull other nodes at the same time. Thus, based on the k-d tree, we introduce a new algorithm with efficient calculation complexity. With our algorithm (3.3), once the coverage ratio is above the threshold ratio, the calculation is terminated. Therefore it is so-called calculation-on-demand algorithm.

Algorithm 3.3 Coverage Improvement with k-d-tree

Require: $B_1, B_2, B_3, \ldots, B_N$, L

Iter := 0

Repeat:

Generate k-d tree T with the point set $\{s_1, s_2, s_3, \ldots, s_N\}$

Estimate Coverage Ratio C // Using MCKD-CRE

If $C >= C_{th}$:

Break

End If

For k **in** [1, N] **do**:

QS = Query T for the neighbors of s_k in range 2L

Calculate force on s_k

Move s_k

End For

Iter := iter +1

Until Max iteration reached.

It should be noted that, we only find the neighbor node of s_k in the distance of $2L$, where L is the sensing range. We consider that if the distance of two nodes are greater than 2L, their sensing regions are not overlapped and thus they need not be moved.

It should be also noted that, in our algorithm, building a static k-d tree from N sensor nodes has the complexity

$O(N \log N)$; Querying an axis-parallel range in a balanced k-d tree takes $O(N^{2/3}+m)$ time, where m is the number of the points in the distance range and m is usually significantly smaller than N. Thus in each iteration, our method take $O(N\log N + N\cdot(N^{2/3}+m)) = O(N^{5/3})$ time. Without k-d tree, it will cost $O(N^2)$ time to calculate each pair of sensors.

In our algorithm, the virtual forces calculated for sensor nodes are in the distance of 2L. The force pushing them apart is given by:

$$F_{ij} = \frac{(x_i - x_j, y_i - y_j, z_i - z_j)}{(a+d_{ij})^2} \tag{16}$$

In the equation, a is a small positive coefficient to avoid that the denominator is zero.

$$f_i = \sum_j F_{ij} \tag{17}$$

$$v_i = \min(F_{\max}, f_i) \tag{18}$$

$$s_i = s_i + Kv_i \tag{19}$$

Note f_i is the total force on s_i, v_i is the speed with upper limitation, and K is a constant to mapping speed to displacement.

In order to increase the coverage ratio, each sensor has to move from overlapped regions to cover the surrounding coverage holes after the initial random deployment. The movements of sensors were adjusted step by step through the algorithm illustrated in algorithm 3.1 so that the coverage ratio is gradually improved. To guide the moving direction of each sensor, we applied a virtual forces based coverage technique for sensor networks according to Eq. (16) – Eq. (19).

4. RESULTS AND DISCUSSIONS

4.1. Grid Quadrature and Monte Carlo Methods' results and analysis

In order to calculate both, real coverage ratio and estimated coverage ratio we performed some simulation experiment and obtained some coverage ratio results which show the accuracy and efficiency of the values obtained by different methods.

Basic Case:

To simplify elaborations let us consider the following Figure 4.

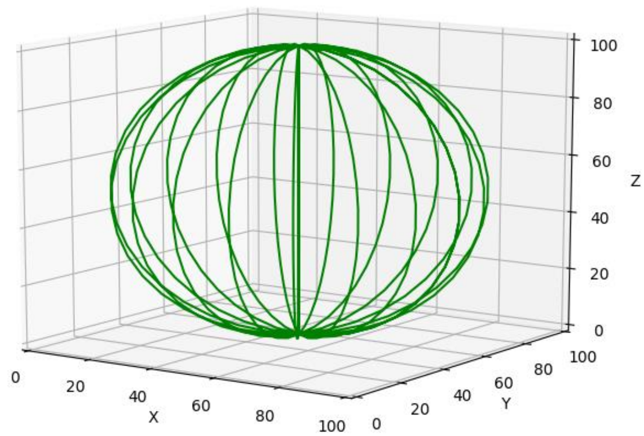


Figure 4 Simulation to aid Calculation of actual coverage ratio

From the figure 4 we have the following dimensions. The length of the cube R is 100 units, the width of the cube R is 100 units, the height of the cube R is 100 units, and the sensing radius of each node is 50 units.

Assume that there is an only one sensor node. Thus the volume of the sensing region is given by:

$$|B| = \frac{4}{3}\pi L^3 = \frac{4}{3}\pi\cdot(50)^3 \tag{20}$$

The volume of the cube R is given by:

$$|R| = 100^3 \tag{21}$$

Now, the coverage ratio is exactly equal to $\frac{4}{3}\pi\cdot(50)^3/100^3 \approx 0.5235$.

By using MC-CRE, GQ-CRE and MCKD-CRE, we can obtain the estimated values close to this actual value. It means all methods are valid for this basic case.

Random Cases with different number of sensor nodes:

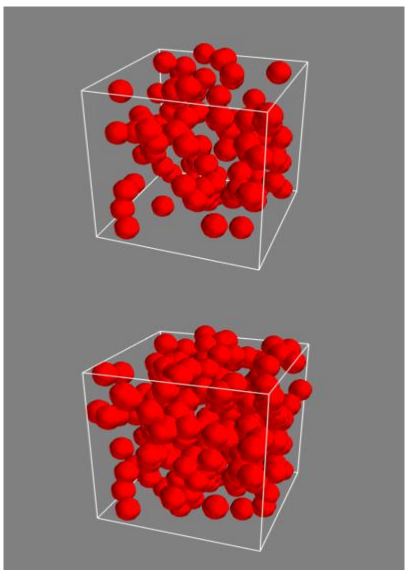
We have already stated in the earlier section how coverage ratio of deployed sensor nodes can be estimated by using different methods.

We considered that, N sensor nodes are deployed randomly in the region R. The simulation parameters are listed in Table 1.

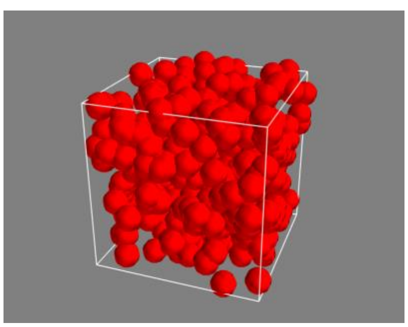
Parameter	Value
Width, length and depth of R	100, 100, 100
Sensing Radius L	10
Deployment	Uniformly random distribution in R
N	100, 200, 400

Table 1 Simulation parameters

We will consider 3 cases N=100, 200 and 400. The sensor nodes are deployed as shown in Figure 5



(a) N=100 (b) N=200

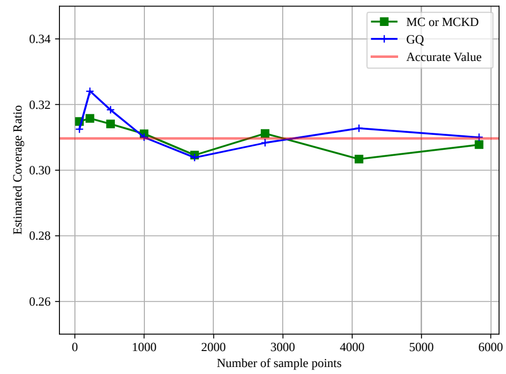


(c) N=400

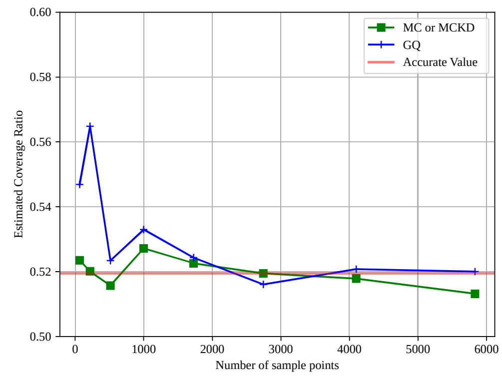
Figure 5 Random sensor deployment cases

We performed MC-CRE, GQ-CRE and MCKD-CRE for these cases. The results are shown in Figure 6 at one of the simulations. Notice that the results of MC-CRE and MCKD-CRE are the same. Their difference lies in the computation complexity which is not discussed in this section.

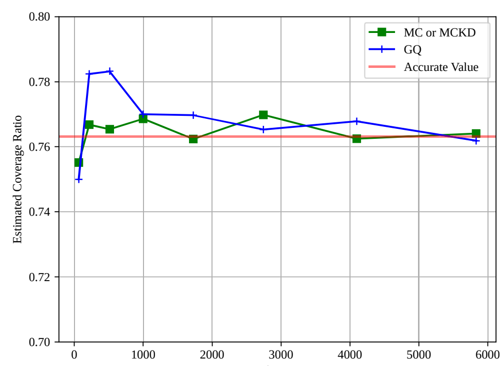
It should be noted that the Figure 6 will be different with different random variables in different simulation iterations. Also the accurate value of the coverage ratio is the result of GQ-CRE with 1,000,000 samples.



(a) N=100



(b) N=200



(c) N=400

Figure 6 Coverage Ratio Estimation for different number of samples and different number of sensor nodes

As shown in Figure 6, results of all methods converge together. Usually, with the same number of sample points, the results of GQ-CRE are better than those of MC-CRE or MCKD-CRE. However, the superiority of GQ-CRE is not obvious. This signifies that, MC-CRE and MCKD-CRE are practical for any number of sample points and also perform well.

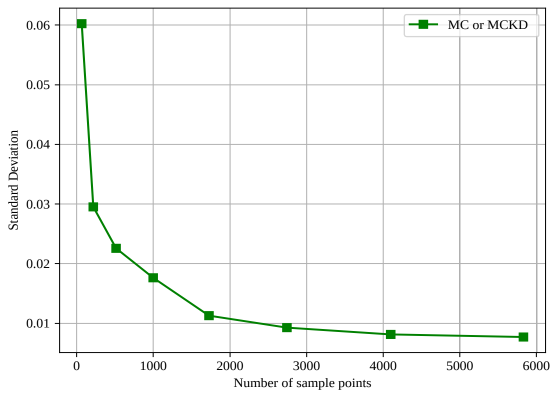


Figure 7 Standard deviation of coverage ratio estimation for different number of samples

As shown in Figure 7, the standard deviation of MC-CRE or MCKD-CRE decrease along with the increase of the number of sample points. It obeys the general convergence rule of Monte-Carlo methods.

Computation complexity:

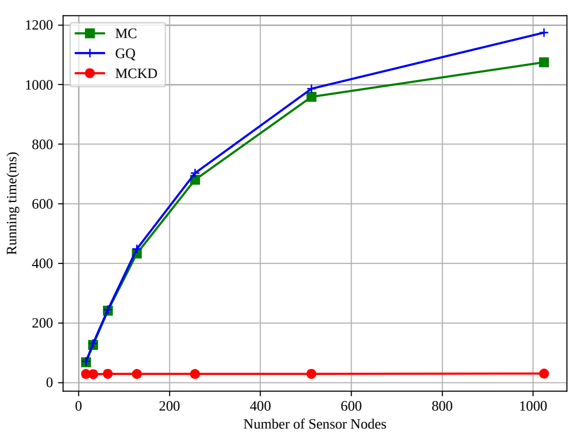


Figure 8 Running time of different methods with M=1000 sample points

We focused on the computation complexity of this method. We have stated that in each iteration i.e. for each sample points, MC-CRE and GQ-CRE should check the sensor nodes, one by one, to determinate whether the sample point is covered by any of the sensor nodes. Such procedure is possible to be terminated once a sensor node covers the sample point; otherwise all the sensor nodes will be checked to determinate no sensors cover the sample points. Thus, with the increase of the number of sensor nodes, the running time of MC-CRE and GQ-CRE will be increased, as shown in Figure 8. All the methods are programmed with Python and tested in a notebook with I7-6600U CPU.

This shows that, the running time of MCKD-CRE is far better than those of MC-CRE and GQ-CRE. Moreover, the running time of MCKD-CRE is almost not increased. The reason partly lies in the fact that, other overloads such as the generation of the random numbers, the Python-C interface for KD-tree, are the major part of the time consumption.

In general, Simulation results show that all methods converge to the right solution. Usually, with the same number of sample points, the results of GQ-CRE are a little better than those of MC-CRE or MCKD-CRE. However, MC-CRE and MCKD-CRE are practical for any number of sample points and also perform well. We also proved that the algorithm MCKD-CRE is rather fast than other methods so as to support large scale networks in an efficient manner

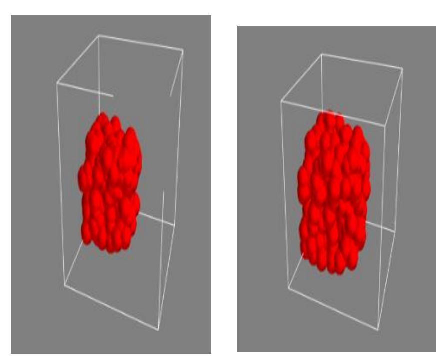
4.2. Results and analysis for the Improved Virtual Force Method based on k-d tree

We used python program to simulate and verify our algorithm. The following diagrams show stepwise enhancement of wireless sensor network coverage in a 3D space. We used 60 iterations to obtain the final improved coverage. Table 2 shows the list of simulation parameters

Parameter	Value
Width, length and depth of R	100, 100, 100
Sensing Radius L	20
N	300

Table 2 Simulation parameters

We will consider an initial status that all sensors are located in the right, lower, internal corner of R, i.e. all of them are located in 1/8 of the total region. The results of iterations are displayed in the Figure 9. We only have shown result of 5 iterations



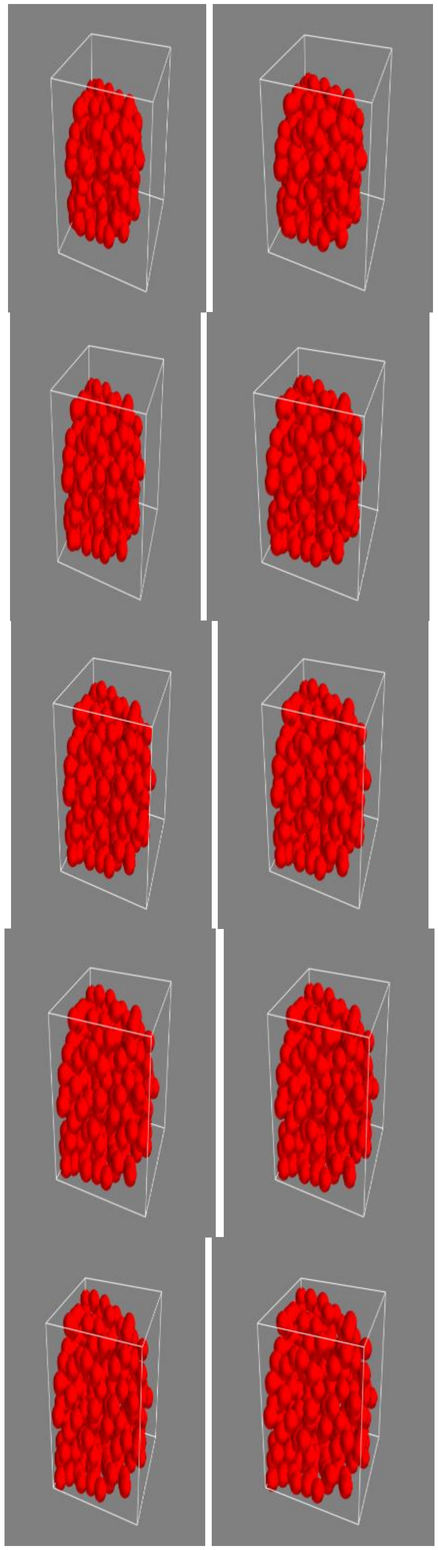


Figure 9 Coverage Enhancement using virtual Force

The coverage ratio is increasing with the number of the iterations, as shown in Figure 10. However, it is interesting to note that the main trends are increasing while at some iteration the coverage ratio undulates. The reason is that the displacement step is constant but not optimal.

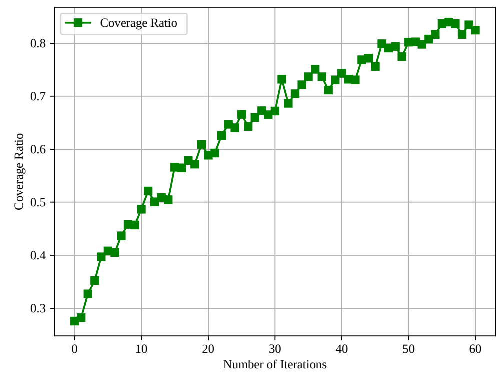


Figure 10 Coverage Ratio versus the number of iterations

Now let us consider another case where sensor nodes are deployed randomly. In this experiment, the number of sensor nodes are N=400 with sensing radius L=10 in a 100x100x100 cube region R. Figure 11 and Figure 12 show the result with different step sizes K. Maximum displacement of each node in one iteration is set to be L.

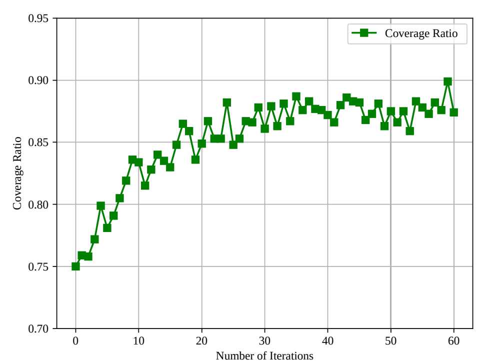


Figure 11 Coverage ratio versus the number of iterations with K=1

The graph summarizes the relationship between coverage enhancement (coverage ratio) and the number of iterations. This means that larger step size help fast convergence to high coverage ratio. However, the flutter of both step sizes during the procedure is obvious. An optimal step size should be studied to enhance our method itself in future. The impact of virtual Force is so important when addressing the issue of coverage since with the application of virtual force we can use the limited number of sensor nodes to cover more space.

However, in our case, the simulation result with our method shows that the coverage ratio is increased with the number of iterations.

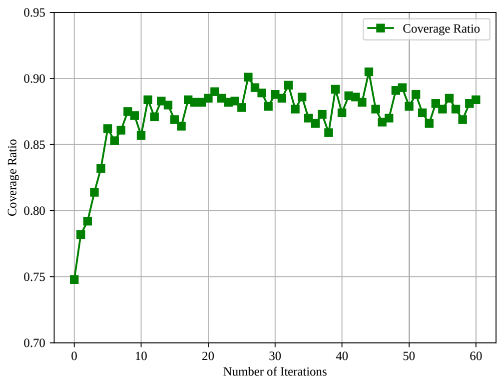


Figure 12 Coverage ratio versus the number of iterations with K=4

5. CONCLUSION

In this study, new coverage model in 3D environment using Monte Carlo (MC) and grid quadrature are presented in detail aiming to convey out the estimations of the coverage ratio which is the core case. Since Monte Carlo method is slow, and grid quadrature is not practical, we design a novel improvement on the Monte Carlo technique based on the k-d tree structure, named MCKD-CRE. Simulations indicate that all methods converge to the right solution. Usually, with the similar number of sample points, the results of GQ-CRE are a little better than those of MC-CRE or MCKD-CRE. However, MC-CRE and MCKD-CRE are practical for any number of sample points and also perform well. We also showed that the algorithm MCKD-CRE is rather faster than other methods so as to support large scale networks in an efficient manner.

We also introduced an improvement of coverage enhancement technique based on virtual force algorithm. Our technique should be utilized in a sensor node network with a sink or a center server. The sink node knows all the location of all other sensor nodes; it calculates the final position of other sensor nodes, and commands all other nodes to move directly to the final position. A virtual force method based on range query capacity of the k-d tree is thus introduced. To calculate the virtual force, only the neighbor nodes in the distance of twice the sensing radius are considered and the forces are always try to push nodes apart. The simulation result shows that, with our method the coverage ratio is increased with the number of the iterations. Generally, with the use of k-d tree data structure, the computation complexity of both the coverage ratio estimation and the coverage enhancement is significantly reduced. Thus it makes both of our methods rather practical in the real-life applications.

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