An Effective Voronoi-based Coverage Enhancing Algorithm in Directional Sensor Networks

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***Abstract*—A directional sensor network is composed of many directional sensor nodes. Unlike conventional omni-directional sensors that always have an omni-angle of sensing range; directional sensors may have a limited angle of sensing range due to technical constraints or cost considerations. Area coverage problem is still an essential issue in directional sensor networks. In this paper, we study the area coverage problem in directional sensor networks. The problem is to maximize the area coverage of a randomly deployed directional sensor network. Each directional sensor can rotate its sensing direction in order to get better coverage in an interested region. In this study, we propose a distributed greedy algorithm that can improve the effective coverage area by using the characteristics of Voronoi diagram. The sensor field is divided into Voronoi cells by the calculation of sensors and the working direction of each sensor is evaluated based on the size and the location of the farthest Voronoi vertex of its surrounding Voronoi cell, respectively. Simulation results show that our proposed algorithm achieves around 5% to 15% better performance than that of previous proposed methods in terms of the area coverage rate.**

Keywords-Directional Sensor Networks; Rotatable Sensors; Area Coverage Problem; Voronoi Diagram.

I. INTRODUCTION *(HEADING 1)*

In recent years, wireless sensor networks have received a lot of attention due to their wide applications in military and civilian operations, such as fire detection [1], vehicle traffic monitoring [2], ocean monitoring [3], and battlefield surveillance [4]. In wireless sensor networks, many works have been done during the last decade. However, most of the past works were always based on the assumption of omni-directional sensors that has an omni-angle of sensing range. In real environment, there are many kinds of directional sensors, such as video sensors [5], ultrasonic sensors [6] and infrared sensors [7]. The omni-directional sensor node has a circular disk of sensing range. The directional sensor node has smaller sensing area (sector-like area) and sensing angle than the omni-directional one. Compared to omni-directional sensors, the coverage region of a directional sensor is determined by its location and orientation. This can be illustrated by the example in Figure 1.

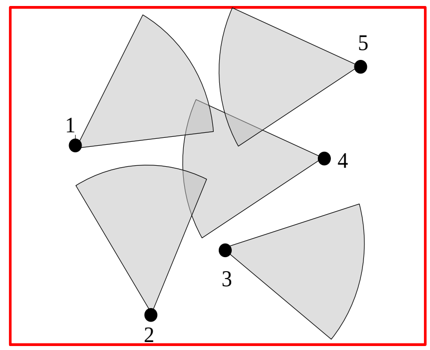

Figure 1. An example of five directional sensors deployed to cover the target region.

Area coverage is a fundamental problem in wireless sensor networks. Sensor nodes must be deployed appropriately to reach an adequate coverage level for the successful completion of the issued sensing tasks [8][9]. However, in many potential working environments, such as remote harsh fields, disaster areas, and toxic urban regions, sensor deployment cannot be performed manually. To scatter sensors by aircraft may result in the situation that the actual landing positions cannot be controlled. Consequently, the coverage may be inferior to the application requirements no matter how many sensors are dropped. For obtaining the better performance in directional sensor networks, directional sensors (e.g., cameras) may be able to rotate around a fixed axis to enhance its coverage in sensing radius [7]-[9]. Therefore, the coverage region of a directional sensor is determined by both its location and its direction of sensing radius. Those sensors that can rotate their sensing directions are called the rotatable sensors. We define the working direction of a sensor as the direction in which it is currently pointing at. We also call the sensing range of a sensor's working direction as its coverage region. The coverage region of different sensors may be overlapped with other sensors after they are randomly deployed. Thus, we need to schedule sensors to face to certain directions to maximize the covered area of the whole network.

In this paper, after sensors are randomly deployed into a target region, our goal is to maximize the total area coverage that can be achieved by rotating each sensor's working direction to proper direction. The problem of working direction scheduling to cover maximal regions, called Maximum Directional Area Coverage (MDAC) problem, has

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been proved to be *NP*-complete [9]. A greedy solution has also been provided through scheduling working directions of sensors. We propose a distributed greedy algorithm for MDAC problem with rotatable sensors to increase the area coverage.

The remainder of this paper is organized as follows: Related work is discussed in Section II. In Section III, the directional sensing model and some preliminaries are proposed. In Section IV, the problem statement is proposed. Section V proposes the distributed greedy algorithm for solving the problem. In Section VI, we present experimental results obtained from different perspectives on the number of sensors, the sensing radius and the sensing angle, respectively. Section VII summarizes our findings.

II. Related Work

Ma and Liu [10] discussed that the number of directional sensors can be deployed to achieve coverage rate p in a distributed directional sensor network (equation (1)). Directional sensors are randomly and uniformly scattered within a given area. Here, R is the sensing radius, S is the given area, and α is the offset angle of the field of view. To be clear, $\alpha R^2/S$ indicates that a directional sensor can monitor given area that is within its sensing region. Therefore, after N directional sensors are deployed, the probability that covers a given area is represented in

$$p = 1 - (1 - \frac{\alpha R^2}{S})^N. \quad (1)$$

In other words, if the coverage rate of a given area is at least p, the number of deployed directional sensors should be represented in

$$N = \frac{\ln(1-p)}{\ln(S - \alpha R^2) - \ln S}. \quad (2)$$

Kandoth and Chellappan [11] proposed a greedy solution called the Face-Away (FA) algorithm to achieve the maximal area coverage rate in the interested region. The *FA* algorithm works in a very simple manner. Each sensor calculates a new working direction that only needs the positions of neighboring sensors. The neighboring sensors of a directional sensor, say *s*, are those sensors located within the circular area centered at *s* with sensing radius *R*. In fact, every sensor should be recognizable from its surroundings when being viewed by its neighbors. Once a sensor is recognized, each sensor must center it in view and record the current working direction.

Li et al. [12] proposed the Voronoi-based centralized approximation (VCA) algorithm and the Voronoi-based distributed approximation (VDA) algorithm of the solution to their proposed optimal coverage in directional sensor networks (OCDSN) problem for covering maximal area while activating as few sensors as possible. Their algorithms are both based upon the so-called boundary Voronoi diagram (BVD). Each sensor will rotate its working direction to cover the largest edge of its surrounding Voronoi region. Thus, the covered area will be increased. However, as the number of sensors increased and non-uniformly deployed into the region, the overlapped area among sensors increased as well.

In [13], the authors proposed two greedy schemes, namely the Intra-cell Working Direction Selection (IDS) and the Inter-cell Working Direction Adjustment (IDA) schemes, which are also based on the Voronoi diagram, to rotate the working direction of each sensor to the direction of the vertices of its corresponding Voronoi cell. The IDS scheme rotates the working direction of each sensor to the Voronoi vertex having the maximum coverage. Then, the IDA approach improves the overlapped coverage between adjacent cells to increase the overall area coverage.

In this paper, we devised a greedy approach for sensors to select their working directions to increase the area coverage. Simulation results show that our proposed algorithm outperforms than previous algorithms, including Face-Away, VDA, and IDS algorithms.

III. Preliminaries

A. Directional Sensing Model

Compared to an omni-directional sensor, which has a disc-shaped sensing range, a directional sensor has a smaller sector-like sensing area and smaller sensing angle, as illustrated in Figure 2. In Figure 2, the sensing region (also called the sensing sector) of a directional sensor is a sector denoted by 4-tuple ($p(x,y)$, r, θ, α). Here, $p(x,y)$ is the location of the sensor node, r is the sensing radius, θ ($0 \le \theta < 2\pi$) is the working direction angle and α ($0 < \alpha \le 2\pi$) is the angle of view. The special case of this model, where $\alpha = 2\pi$ can be described as omni-sensing model.

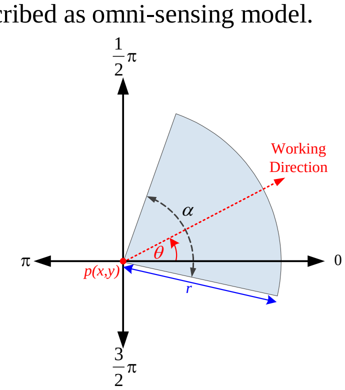

Figure 2. The directional sensing model.

We illustrate the characteristic of directional sensors:

- Each directional sensor is homogeneous, such as: sensing angle, sensing radius, and communication radius.
- Each directional sensor can sense only one limited angle of omni-direction.
- Each directional sensor is fixed and can rotate arbitrary angle in sensing region.
- The communication radius is twice than the sensing radius such that sensing neighbors can reliably communicate.

B. Voronoi Cells

Voronoi diagram, a well-known data structure in computational geometry [14], partitions a plane into a set of convex polygons such that all points inside a polygon are closest to only one site. This study used the Voronoi diagram structure and divided the sensing area into Voronoi cells according to the positions of deployed sensors, as shown in Figure 3.

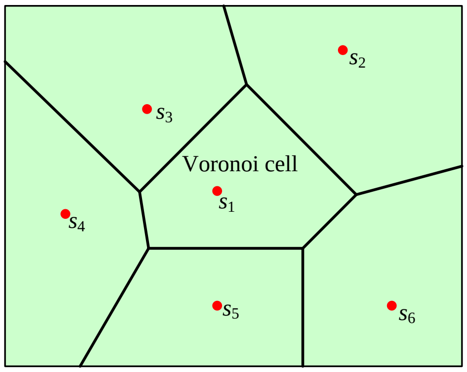

Figure 3. Dividing sensing area into Voronoi cells associated with sensors.

The construction effectively produces polygons with edges that are equidistant from neighboring sites. Those line segments that form the boundaries of Voronoi cells are called the Voronoi edges. The endpoints of these edges are called the Voronoi vertices.

IV. PROBLEM STATEMENT

Usually a numerous of sensors are randomly deployed into a target region for covering the area as much as possible in order to reach an adequate coverage level for further applications. However, it is not easy to obtain optimum coverage because of the overlapped covered area. The defect in using centralized algorithms for this problem is that a node with powerful computing resource is required for calculation. Moreover, massive node information must be transmitted to the sink node in multi-hop mode, thus consuming a lot of sensor network transmission resources. On the contrary, the distributed algorithms do not need global information but only local information gathered from neighboring sensors for calculation, thus consuming fewer calculation and network transmission resources. In addition, the distributed algorithm is more practical to implement real-time response or adjustment according to the dynamic environment change.

For numerous directional sensors randomly distributed in the sensing field, the field coverage problem is a basic and important problem without optimal solution. This study used the distributed greedy algorithm to obtain the near optimum solution. Based on the Voronoi cells structure, each sensor uses the vertices of its cell as the candidate targets of working direction. The working direction is selected and adjusted and the original direction of each sensor is changed on the two principles: (1) to enlarge the area covered by the sensor while reducing the sensors overlapped coverage with neighboring sensors as much as possible; (2) to avoid the sensor coverage being outside the sensing field as possible; so that the overall target area coverage is improved.

Now, we formally state our problem as follows:

Problem: Randomly deploying N directional sensors with sensing range R_S, communication range R_C and sensing angle α in a given target sensing region where $R_C = 2R_S$ and $0 < \alpha \leq 2\pi$, we are asked to devise a distributed algorithm for each sensor to adjust or rotate its working direction so that the total area coverage is maximized.

V. PROPOSED SENSOR DIRECTION CONTROL SCHEME

In this section, the algorithm corresponding to the two major principles of selecting working direction will be described respectively, which are Working Direction Selection scheme and Out-of-Field Coverage Recovery procedure.

A. Working Direction Selection

Although we all know that a sensor can rotate its sensing direction to increase the coverage, we still do not know which direction is the best for a sensor to rotate. Therefore, the main idea of our proposed algorithm is to determine the most possible direction of a sensor to rotate so that after the rotation, the overlapped region with other sensors is minimized. The following is our strategy for finding the rotating direction. According to [13], the sensor having the optimal sensing quality is to cover the most area within its corresponding Voronoi cell. Thus, our first step is to determine which direction is the most likely for a sensor to cover within its Voronoi cell zone. To do so, when each sensor completes the construction of its Voronoi cell, the vertices of the cell are used as preliminary working direction candidates. The sensor calculates respective coverage sizes within the cell zone of aligning direction with each vertex of its Voronoi cell and selects the vertex having the maximum coverage and the minimum overlapped with other sensors within the cell zone as its working direction. In other words, this selection will decide the most effective or non-overlapped sensing area from the position of sensor.

Obviously, the decision for a sensor of selecting the most effective or non-overlapped sensing area depends on the directions of its neighboring sensors. If the working directions of all neighboring sensors are determined, the sensor can easily determine its working direction to the direction that has no overlapped area with its neighboring sensors. However, if some neighboring sensors have not decided their working directions yet, then there may have chances to overlap with these undecided sensors. Therefore, the sequence of sensors for determining their working directions will affect the performance of reducing the overlapped area. For determining the decision sequence, we consider the average edge length of the Voronoi cell of each sensor. The average edge length of each sensor is calculated as the length of all edges in its surrounding Voronoi cell divided by the number of its neighboring sensors. Therefore, it can be seen that if the average edge length is small, the sensor may have more neighboring sensors than those with larger average edge lengths. In this case, it is better for the sensor to determine its working direction before other sensors since once it decided, all the neighboring sensors can easily determine their working directions by avoiding the area covered by the decided sensor.

Here, we describe our proposed greedy algorithm for MDAC problem. The proposed algorithm is called the *Voronoi-based Minimal Size First* (VMSF) algorithm. In our proposed algorithm, when each sensor completes the construction of its Voronoi cell, the sensor calculates the average edge length of its surrounding Voronoi cell as the priority of rotation. It should be noticed that, as we mentioned above, the smaller the average edge length is, the higher the priority will be. In other words, if the average edge length of a sensor is small, meaning that the sensor may have many neighbors, then the sensor has higher priority to be scheduled for rotation. Once a sensor has determined to rotate, the new direction can be obtained by finding the vertex of its Voronoi cell with largest uncovered and non-overlapped region.

B. Out-of-Field Coverage Recovery

The positions of a part of deployed sensors may be close to the boundary of the target region. The working direction of these sensors may face toward the boundary so that most of coverage is outside the sensing field, wasting the coverage of sensors of the sensing field. Therefore, after the working direction selection procedure, this study implements additional Out-of-Field Coverage Recovery procedure on these sensors near the boundary. Figure 4 shows an example with three cases. The working direction of an out-of-field sensor can be recovered by rotating the working direction towards the inside of sensing field, as shown in Figure 5, so that the working direction angle θ of s_i should conform to θ_1 or θ_2.

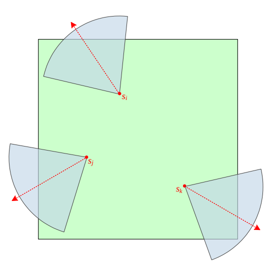

Figure 4. An example of out-of-field coverage.

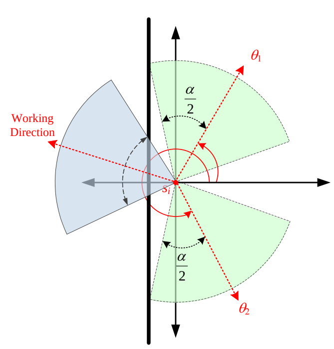

Figure 5. Direction adjustment for of Out-of-Field Coverage Recovery.

The pseudo-code of the our proposed VMSF algorithm is shown in Figure 6.

Algorithm: Voronoi-based Minimal Size First algorithm

I. Initialization Phase (only performed once)

Send a coverage message containing sensor ID, initial working direction, and location of sensor s_i and wait a period of time for collecting the information from sensing neighbors

Calculate the Voronoi diagram and determine the priority value P_i and broadcast the value

Collect the priority values from all neighboring sensors and go to the **Decision Phase**.

II. Decision Phase

```
while true do
    Find the highest priority values, denoted as P_max, among neighboring sensors
    if P_i > P_max then
        Find the point, say A, on the Voronoi cell with maximal uncovered region and non-overlapped region
        Rotate its working direction to point A, set its priority value to 0 and send a scheduled message containing ID and priority value to its sensing neighbors
        Exit the while loop
    else
        if P_i = P_max then
            Wait for a random duration or a scheduled message sent by a sensor, say s_j, is received
            if no scheduled message received then
                Find the point, say A, on the Voronoi cell with maximal uncovered and non-overlapped region
                Rotate its working direction to point A, set its priority value to 0 and send a scheduled message containing ID and priority value to its sensing neighbors.
                Exit the while loop
            end if
        else
            Wait until a scheduled message sent by a sensor, say s_j, is received
        end if
        Set the status of s_j as "scheduled" and update its priority P_i according to its remaining "unscheduled" neighboring sensors
        Send P_i to its "unscheduled" neighboring sensors
        Collect the priority values from all of its "unscheduled" neighboring sensors
    end if
end while
```

Figure 6. The proposed sensor direction selection algorithm.

In the next section, we will present the performance of our proposed sensor movement algorithm.

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VI. Simulation Results

This section describes the parameters and performance effects of different perspectives on our proposed algorithm, compared with previous algorithms. We conducted our experiments on a computer with 3.0 GHz CPU and 4GB memory. All experiments are done in C# on .NET platform. Our simulation network consists of 50 to 200 directional sensor nodes placed randomly within a 500 *m* x 500 *m* area. Every experiment was repeated 100 times and the recorded data was averaged over those runs. Table 1 lists the values of the common parameters used in all the experiments.

TABLE I. Experimental parameters

Parameters	Description
Network Size	500 × 500 (m^2)
Sensing Radius	30*m*, 35*m*, …, 60*m*
Sensing Angle	60°,80°, …, 180°
Number of Sensors	50, 75, …, 200

The main goal of our simulation is focused on the comparison of the performance of our proposed VMSF algorithm, random approach (Random) in which each sensor select its working direction randomly, FA, VDA and IDS algorithms, in terms of the coverage rate. The coverage rate p is defined as the ratio of the total covered area by all sensors over the network size. We evaluate the effects of our algorithm on three different perspectives. First, we examine the effect that the number of sensors N makes to the improvement of coverage rate p. Second, we evaluate the effect that the sensing radius improves the coverage rate p. Third, we examine the effect that the offset angle makes to the improvement of coverage rate p.

A. Coverage rate vs. Number of sensors

This experiment evaluates the effect that the number of sensors N makes to the performance of coverage rate p of Random approach, FA, VDA, IDS, and VMSF algorithms respectively. The sensing radius R is set to 50m and the sensing angle α is set to 120°. The result is shown in Figure 7.

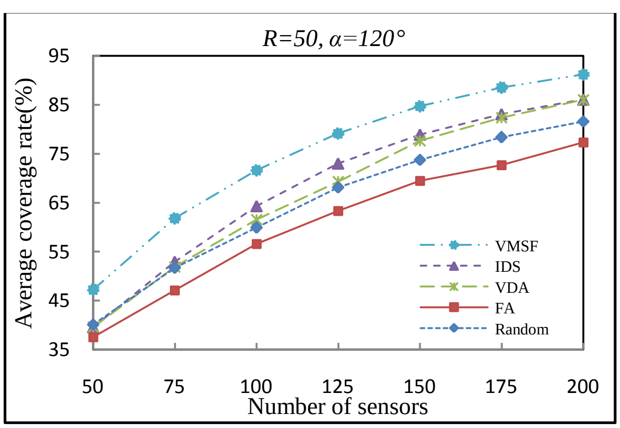

Figure 7. Coverage rate vs. number of sensors with R = 50m and α = 120°.

In Figure 7, we can see that our proposed VMSF algorithm outperforms all other approaches. For example, when the number of sensors is 200, the sensing radius is 50m and the sensing angle is 120°, the coverage rates of Random approach, FA, VDA, IDS, and VMSF algorithms are 77.31%, 74.48%, 83,18%, 84.09%, and 92.42% respectively. Thus, the VMSF algorithm outperforms other approaches. This is because that VMSF algorithm can achieve the less overlapping area and the order of sensors chosen to rotate will influence the performance of coverage rate. Therefore, our proposed VMSF algorithm can get the most improvement on coverage rate among all algorithms.

B. Coverage rate vs. Sensing radius

This experiment examines the effect that sensing radius R makes to the performance of coverage rate p of Random approach, FA, VDA, IDS, and VMSF algorithms respectively. The sensing angle is set to 120°. The number of sensors is set to 200. The result is shown in Figure 8.

In Figure 8, we can see that our proposed VMSF algorithm outperforms all other approached. For example, when the number of sensors is 200, the sensing radius is 60*m* and the sensing angle is 120°, the coverage rates of Random approach, FA, VDA, IDS, and VMSF algorithms are 86.89%, 86.12%, 90.58%, 93.23% and 96.91% respectively. Thus, the VMSF algorithm performs better than other approaches from 3.68% to 10.02%. This is because that our VMSF algorithm can achieve less overlapped region and higher coverage rate. We also note that, as the sensing radius increases, the coverage rates of all algorithms rise. This is obvious since the greater the sensing radius is, the more sensing area can be obtained.

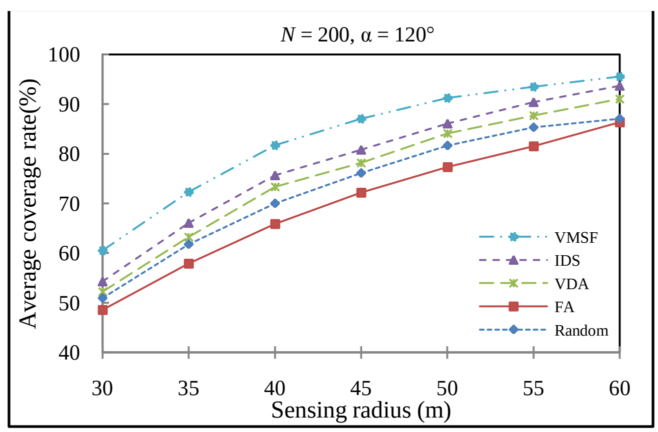

Figure 8. Coverage rate vs. sensing radius with N = 200 and α = 120°.

C. Coverage rate vs. Sensing angles

This experiment evaluates the effect that sensing angle α makes to the performance of coverage rate p of Random approach, FA, VDA, IDS, and VMSF algorithms respectively. The sensing radius is set to 50*m*. The number of sensors is set to 200. The result is shown in Figure 9.

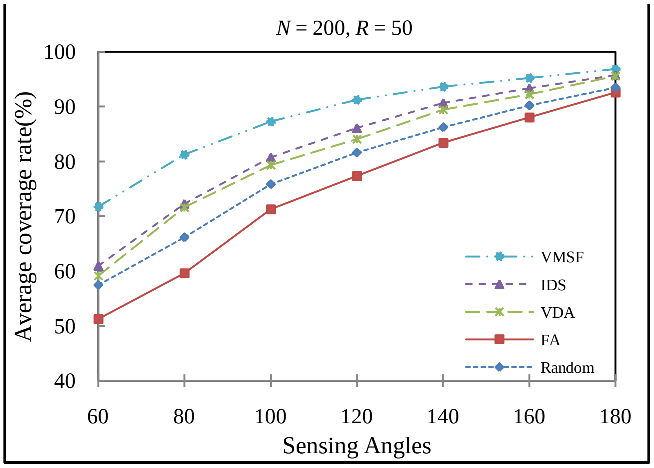

Figure 9. Coverage rate vs. sensing angles with R = 50m and N = 200.

In Figure 9, we can see that our proposed VMSF algorithm outperforms all other approaches. For example, when the number of sensors is 200, the sensing radius is 50*m* and the sensing angle is 120°, the coverage rates of Random approach, FA, VDA, IDS, and VMSF algorithms are 78.12%, 82.31%, 84.92%, 86.53%, and 91.68% respectively. Thus, the VMSF algorithm performs 5.15% better than the IDS algorithm. This is because that our proposed VMSF algorithm can achieve less overlapped area and higher coverage rate. We also note that, as the sensing angle α increases, the coverage rates of all algorithms rise. However, once the value of α exceeds a certain value (≥ 140° in this experiment), the increasing coverage rate becomes flat rising. This is because, when the network density and sensing radius are fixed, the larger the sensing angle is, the smaller the possibility of uncovered area becomes.

VII. CONCLUSIONS

In this paper, we investigate the Maximum Directional Area Coverage (MDAC) problem in which we are asked to maximize the area coverage by scheduling the sensing direction or rotating the working direction of each sensor. We propose a distributed greedy algorithm, called the Voronoi-based Minimal Size First (VMSF) approach, which is based on the size of the corresponding Voronoi cell and the area of the overlapped region between directional sensors. Simulation results show that our proposed algorithm achieves better performance around 8% to 15%, 4% to 10%, and 5% to 13% than those of previous algorithms in terms of coverage rate on different number of sensors, sensing radius and sensing angles, respectively.

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