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Targets Coverage Algorithm based on Three-dimensional Directional Sensing Model

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Abstract. *In traditional wireless multimedia sensor networks, almost all coverage control algorithms are based on two-dimensional directional sensing models. However, they cannot accurately characterize the actual perception capability of multimedia sensor. To remedy this deficiency, a novel 3D directional sensing model with tunable orientations has been proposed in this paper. In addition, we apply differential evolution algorithm to optimize main perceptional directions in order to solve targets coverage problem, which focuses on finding the minimum subset of sensor nodes to cover all the targets. The extensive simulations show the effectiveness and advantage of our proposed 3D sensing model and targets coverage method.*
Keywords: Wireless multimedia sensor networks, 3D directional sensing model, Targets coverage problem, Differential evolution algorithm

1. **Introduction.** Wireless multimedia sensor networks (referred as WMSNs) have successfully been applied in many diverse domains of engineering, such as industrial, military, transport and logistics, environmental monitoring et al., [1-6]. Due to their vast and significant applications, WMSNs have become a hot spot for researchers. In order to convenient mathematical analysis, a few papers have indeed brought out the simplified two dimensional (referred as 2D) sensing models to characterize wireless multimedia sensor nodes. Ma first presented a directional sensing model rooted from the concept of field of view cameras, which is a sector denoted by 4-tuple and is allowed to work in several directions [7]. Thereafter, Makhoul et al., and Adriaens et.al employed a relevant triangle and a polygon to characterize directional sensing ability respectively [8, 9], in which the main indicative parameters were similar to the sector-sensing model proposed by Ma. Among these sensing models, the sector-sensing model proposed by Ma was the simplest; therefore it has become the most widely used among academics. Although the above-mentioned 2D sensing models based frameworks are analytically more tractable in designing and evaluating the directional sensor networks, they cannot accurately characterize the practical application scenes. In fact, sensor nodes are placed in a real 3D

physical world. Therefore, the sensor nodes' sensing model should consist of 3D structures, although at present, only two types of 3D directional sensing models have been proposed in [10] and [11], which have been denoted by 5 similar tuple. Although they can characterize sensor's space sensing abilities in some aspects, some characteristics are still in incongruent to people's subjective cognitive as below. The sensing range in [10] is the same with the locations of sensor nodes changing; in fact, the height of sensor determines its sensing range to some extent. When comparing this model, the work [11] is redefined as the maximum field of view in horizontal and sensing range changing with the height of the sensor deployed to form a novel model. However, the offset angle of main sensing direction in Z-axis is not taken from 0 to $\pi/2$. Based on these 3D models, only individual several typical coverage problems in the 2D plane are extended to the 3D scene, including the cover-enhancing issue and the deployment issue, taking into account the K-coverage and accuracy, respectively. Based on the above cited literature, we find the exiting 3D directional sensing models will not continue to characterize the sensor's space sensing abilities especially accurately, and a typical targets cover problem, which focuses on minimizing the size of the subset of sensors to monitor all targets based on 3D sensing models, has not been discussed. Therefore, we design a novel 3D directional sensing model to derive to characterize sensor node accurately and establish a targets coverage scheme based on this model. The main idea of our targets coverage scheme is to adjust the main sensing directions, based on differential evolution algorithm. Numerical results demonstrate that our algorithm requires fewer sensors to cover all targets than additional four methods in all coverage glitches, including the random deployed scheme, Simulated Annealing (referred as SA), Genetic Algorithm (referred as GA), and Particle Swarm Optimization algorithm (referred as PSO).The rest of this paper is organized as follows. Section 2 defines the 3D directional sensing model for sensor node. Section 3 proposes a targets-coverage optimization approach based on differential evolution algorithm. Section 4 conducts the performance evaluations for our proposed model and algorithms. The paper concludes with Section 5.

2. **An New Three-dimensional Directional Sensing Model.** Different from the previous 2D directional sensing model, which is viewed as a sector in a 2D plane, the 3D directional sensing model is dependent on the characteristics of a PTZ(Pan Tilt Zoom) camera. Existing 3D directional sensing model cannot accurately characterize the practical application scenes, in which the sensing range does not change with the height of sensors deployed and field of view in horizontal is asymmetry in main sensing direction. It results from R and α is defined irrelevantly. Therefore, a novel 3D directional sensing model is proposed in this paper based on existing studies, and some details are described as follows. **Definition 1:** 3D directional sensing model is denoted 5-tuple $(P, R, \vec{V}, \alpha, \beta)$, where $\boldsymbol{P}$ is the location of wireless multimedia sensor node with 3D space, described as (x, y, z), $\boldsymbol{R}$ is the maximum radius of clear sensing for sensor node, α and β are the maximum field of view in horizontal and in vertical respect, $\vec{V}$ is the main sensing direction of node, which can be changed by the horizontal angle γ (perpendicular of $\vec{V}$ in X-Y plane), and vertical angle θ (perpendicular of $\vec{V}$ in X-Z plane), $\vec{V}$ is redefined as $\vec{V} = (\gamma, \theta)$. Without the loss of generality, γ is uniform distribution in $[0, \pi]$, θ is taken from $[0, 2\pi]$.

Fig.1 illustrates our proposed sensor node's 3D directional sensing model, where $\overrightarrow{PV} = C$, $\angle P'PV = \gamma$, $\angle VP'N = \theta$, $\angle VP'D_1 = \alpha$, $\angle VPO = \beta$, and $P'D_6 = R$.

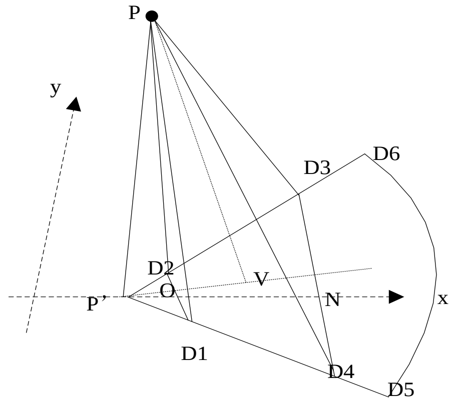
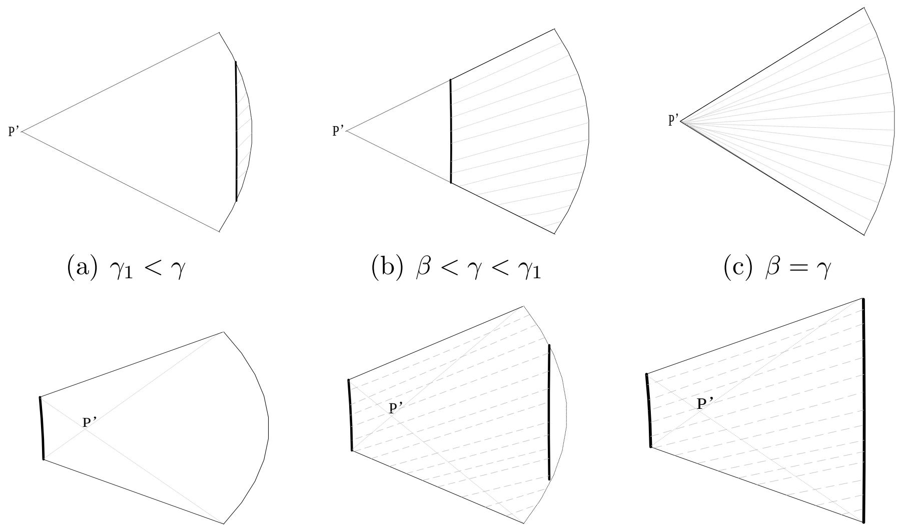


FIGURE 1. new 3D directional sensing model

From Fig.1, we can see that the sensing range in horizontal will change with the height of P, and α is symmetric about perpendicular of main sensing direction, which indicates this model obeys the coverage rules of multimedia sensor.

According to the definition of the 3D model, the different deviate angle γ will lead to the projection scene of 3D directional sensing model in horizontal plane (see Fig.2) and the corresponding conditions of targets covered (the details will be illustrated in **section 3.1**) differently due to the limit of α and β. where γ_1 and γ_2 correspond to the two kinds



(a) $\gamma_1 < \gamma$ (b) $\beta < \gamma < \gamma_1$ (c) $\beta = \gamma$

(d) $\gamma_2 - \beta < \gamma$ (e) $\gamma_1 - \beta < \gamma < \gamma_2 - \beta$ (f) $\beta = \gamma$

FIGURE 2. horizontal plan in all situations

of critical status respectively described as Fig.3, and PN=R, PO_2=R.

Where γ_1 and γ_2 are calculated as Eqs.(1) and Eqs. (2)

$$\cos\gamma_1 = \cos\angle P'PO_1 = \frac{PP'}{PO_1} = \frac{z}{\sqrt{R^2 - z^2}\cos\alpha} \tag{1}$$

$$\cos\gamma_2 = \cos\angle P'PO_2 = \frac{PP'}{PO_2} = \frac{z}{R} \tag{2}$$

3. Targets Coverage Algorithm based on the Proposed Sensing Model.

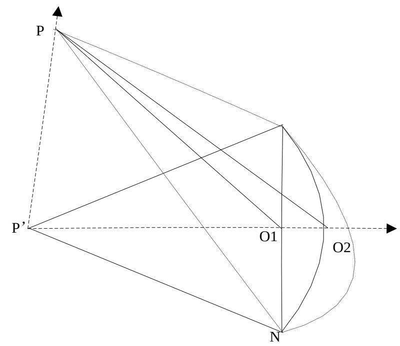


FIGURE 3. Critical condition

3.1. **Targets Coverage Problem and Targets Coverage Conditions.** The objective of the targets coverage problem is to find a minimum subset of sensors within the sensor network that can monitor all targets. Therefore, we should judge whether a sensor node covers a target. Here, most complex coverage situation in Fig.2(e) is taken as an example to explain how to judge whether a target $T(X', Y')$ is covered by a particular sensor. Firstly, we should know the space model of sensor node in question, described as Fig.4.

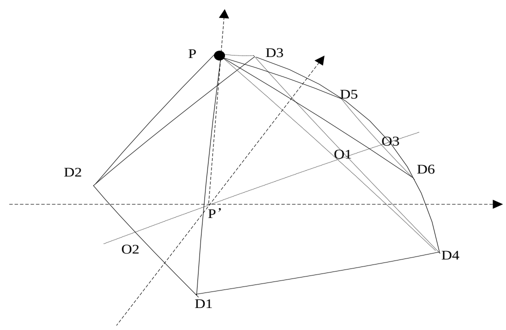


FIGURE 4. Three-dimensional projection

where $PP' = z$, $\angle P'PO3 = \gamma+\beta$, $\angle P'PO1 = \beta-\gamma$, $\angle D_1PO_1 = \angle N_2PP' = \angle D_4PO_2 = \angle D_6PO_3 = \alpha$, $PD_3 = PD_4 = R$.

Certain conditions must be met if the target is covered by the particular sensor as follows. Given a target $T(X', Y')$, the projective point P' of a sensor node P in X-Y plane, the relative coordinate of the target $T(X', Y')$ about P' is $T'(X'-x, Y'-y) = T'(x_0, y_0)$.

(1) the following condition is met.

$$x_0^2 + y_0^2 \leq R^2 - z^2 \tag{3}$$

(2) The target is on the right of directed line segment D_5D_6, D_2D3, and D_1D_2, and on the left of D_1D_4.

Here, the target is taken as $T(X', Y')$ and the directed line segment D_5D_6 as an example to explain how to judge whether a target is on the right of the directed line segment. Given $T' = (X', Y')$, the coordinates of D_5 and D_6 are described as $D_5\,(x_{D_5}, y_{D_5})$ and $D_6 \quad (x_{D_6}, y_{D_6})$, if D_1 calculated as Eqs. (4) is more than 0, the target T is on the right of directed line segment D_5D_6, and vice versa.

$$\begin{cases} A_1 = y_{D_6} - y_{D_5} \\ B_1 = x_{D_5} - x_{D_6} \\ C_1 = x_{D_6}y_{D_5} - x_{D_5}y_{D_6} \\ D_1 = A_1x_0 + B_1y_0 - C_1 \end{cases} \tag{4}$$

According to this method, we need to know the coordinates of those vertexes of Fig.4 calculated as follows, in order to accurately judge the position relation between each point and each relative directed line segment:

$D_1\,(P'D_1\cos(\pi+\theta+\alpha), P'D_1\sin(\pi+\theta+\alpha))$
$D_2\,(P'D_1\cos(\pi+\theta-\alpha), P'D_1\sin(\pi+\theta-\alpha))$
$D_3\,(P'D_4\cos(\alpha+\theta), P'D_4\sin(\alpha+\theta))$ $D_4\,(P'D_4\cos(\theta-\alpha), P'D_4\sin(\theta-\alpha))$
$D_5\,(P'D_6\cos(\rho+\theta), P'D_6\sin(\rho+\theta))$ $D_6\,(P'D_6\cos(\theta-\rho), P'D_6\sin(\theta-\rho))$

where $P'D_4 = \sqrt{R^2 - z^2}$, $P'D_1 = \frac{z\tan(\beta-\gamma)}{\cos\alpha}$.

3.2. **Targets Coverage Algorithm.** As described in section 2, a wireless multimedia sensor node has a smaller sensing range than an omnidirectional sensor. It is possible that some targets will not be hit when sensors are deployed randomly. Therefore, we need to schedule sensors in the network to face certain directions in order to cover the targets to satisfy targets coverage requirements. As depicted above, the aim of the targets coverage problem is to minimize the subset of directional sensors by properly choosing the sensors and the corresponding main sensing directions of each sensor to guarantee all the targets covered. Therefore, for our proposed 3D sensing model, finding the group of sensing orientation $[(\gamma_1, \theta_1), (\gamma_2, \theta_2), \cdots, (\gamma_n, \theta_n)]$ (n is the number of sensors deployed randomly) with minimum subset to monitor all targets is the key to answering these problems.

Main sensing directions adjustment is mutual restraint by the adjacent sensor nodes, and is thus seen as a NP-Hard problem. Differential evolution algorithm (DE)[12] is typically and effectively adopted for this problem. Steps of our targets coverage algorithm based on the proposed sensing model and DE are elaborated as follows.

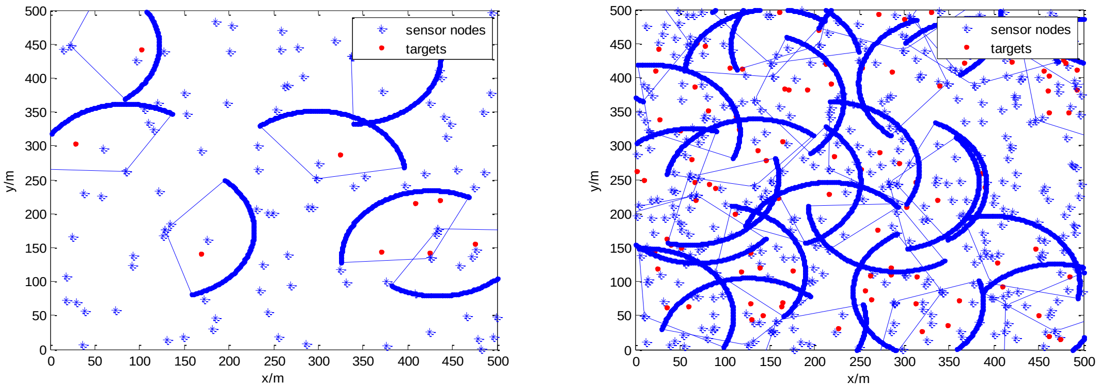
Step 1: Parameters initialization: Initiate sensor nodes' homogeneous information α, β, $\boldsymbol{R}$ and heterogeneous information $[(P_1, \gamma_1, \theta_1), (P_2, \gamma_2, \theta_2) \cdots (P_M, \gamma_M, \theta_M)]$, information of scene such as max x, max y, and parameters of ABC such as population size $\boldsymbol{NP}$, iterations $\boldsymbol{Maxiter}$,etc.
Step 2: Randomly deploy targets in the scene.
Step 3: Population initialization: randomly generate a population about main sensing directions.
Step 4: Calculate fitness function of each individual in the population according to the following method. Set the maximum number of iterations, in each cycle; generate a random sequence about sensor nodes. According to this sequence, the sensors which make the covered targets increase are placed to the subset of sensors one by one until they can cover all the targets.
Step 5: If the maximum number of iterations has not been reached, then go to Step 7. Otherwise, go to Step 11.
Step 6: Mutation: this operation creates mutation vectors based on the current parent population and different mutation strategies as "DE/current-to-best/2" frequently used in literature.
Step 7: Crossover: After mutation, a "binary" crossover operation forms the trial vector, and a new individual is generated.
Step 8: The selection operation selects the better one from the parent vector and the new vector according to their fitness values.
Step 9: Output the current global best fitness value, and corresponding individual, including kept sensor nodes and corresponding main sensing directions including tilt angles and deviate angles.

4. **Experiments and Results.** To state the advantages and effectiveness of our novel three-dimension sensing model and targets cover algorithm, computer simulations were

implemented using MATLAB 2007. All of our experiments are performed on a Windows 7 workstation equipped with a 1.86GHz CPU and 1GB memory. Our coverage problems focus on the square region $S = 500 \times 500m^2$, the multimedia sensor nodes parameters $\alpha = 60°$, $\beta = 60°$, where the height z is randomly taken from 5m to 12m, and the tilt angles are randomly taken from $[0, \pi/, 2]$, while the deviate angles are randomly taken from $[0, 2\pi]$.

In this section, the experiments are divided into two parts as follows. First, we intend to verify if the proposed method is truly efficient in targets coverage problems. Second, we compare the performance of the proposed method with additional four methods, including the random method, Simulated Annealing (referred as SA), Genetic Algorithm (referred as GA) and Particle Swarm Optimization algorithm (referred as PSO), in terms of solution precision and stability in many coverage problems.

4.1. **Verify the Efficiency of the Proposed Targets Cover Method.** We utilize two targets cover problems to illustrate the effectiveness of our 3D sensing model and algorithm. The one coverage problem consists of 10 sensor nodes and 10 targets deployed randomly in area of S, and the other includes 400 sensor nodes and 10 targets. Fig.5 shows the locations of the targets and sensor nodes in these cases and the simulation results of our model and algorithm in subsequent cases. As shown in Fig.5, after the



(a) small-scale targets coverage problem (b) big-scale targets coverage problem

FIGURE 5. Three-dimensional projection

adjustment of sensor nodes, only 7 or 31 sensor nodes were needed in order to cover all targets. This is notably less than the original number of sensors required, which illustrates the effectiveness of the proposed 3D sensing model and targets cover algorithm.

4.2. **Comparison of the Proposed Method with Additional Four Methods in many Coverage Problems.** In order to further verify the effectiveness of the proposed algorithm, we compare the performance with random method, SA, GA and PSO in many coverage glitches, through changing the number of initial nodes and sensors. To make the comparison fair, the fitness values of these methods are subsequently calculated in the random method in section III B, the populations for these algorithms over each problem instance are initialized using the same locations of targets and sensor nodes, and the same termination criterion (the maximum numbers of function evaluations (MAX_FEs)). In addition, each algorithm is implemented 10 times separately in order to avoid a positive outcome caused by randomness. In our experiment, MAX_FEs of all algorithms is equal to 5000, and the population size of SA, GA and PSO is set to 50. The results were shown in Table 1, where M and N represent the number of targets and sensors respectively.

Table 1. Performance comparison of five algorithms in many coverage problems

algorithm	performance	M=25			M=75			M=125		
		N=150	N=250	N=350	N=150	N=250	N=350	N=150	N=250	N=350
Random method	Best	19	18	18	35	34	34	46	46	45
	mean	20.4	19.2	18.8	36.2	35	34.8	46.7	47.1	45.8
	worst	21	20	20	37	36	36	48	48	47
	variance	0.8	0.6	0.7483	0.7483	0.6325	0.8718	0.6403	0.7	0.6
SA	Best	14	13	13	29	29	28	**37**	37	37
	mean	15.4	14.4	13.8	30.2	29.8	28.6	38.6	38.2	37.7
	worst	17	15	15	31	31	31	39	39	39
	variance	1.1136	0.4899	0.7483	0.6	0.6	0.8	0.8	0.7483	0.6403
GA	Best	13	13	**12**	29	28	**27**	**37**	37	37
	mean	14.8	13.7	13.5	30	28.7	28.1	37.9	37.7	37.7
	worst	16	15	15	31	30	29	39	39	39
	variance	0.6	0.6403	1.0247	0.8944	0.6403	0.7	0.8307	0.6403	0.781
PSO	Best	13	13	**12**	29	**27**	**27**	**37**	37	**36**
	mean	14.1	13.6	12.8	29.7	27.9	27.7	37.6	37.6	37.5
	worst	15	15	14	31	29	29	39	38	38
	variance	0.8307	0.4899	0.6	0.6403	0.3	0.6403	0.6633	0.4899	0.6708
The proposed algorithm	Best	**13**	**12**	**12**	**28**	**27**	**27**	**37**	**36**	**36**
	mean	13	12	12	29.3	27.7	27.4	37.8	36.9	36.7
	worst	13	12	12	30	28	28	39	38	37
	variance	0	0	0	0.6403	0.4583	0.4899	0.6	0.8307	0.4583

As shown in Table.1, we can obtain the following conclusions. First, when the size of sensor nodes deployed initially is the same, as more targets are to be covered, the size of the subset of sensor nodes covering all targets consequently increases. This is parallel to the true situation, which shows that the proposed 3D directional sensing model can characterize the actual perception capability of multimedia sensor node to some extent. Second, the size of the subset of sensor nodes calculated by the proposed method is less than the other four methods tested in each coverage problem. As more complex the coverage problem is. Superiority of the proposed method significantly increases. It can be concluded that the proposed method in this paper has advantages in terms of the solution precision and stability.

5. **Conclusions.** In this paper, a new 3D directional sensing model has been proposed to characterize the actual perception capability of multimedia sensor node more accurately. A target cover algorithm, based on this model, was developed in order to reduce the size of the subset of sensor nodes covering all targets, which adjusts nodes' sensing direction by tilt angle and deviate angle optimization. The extensive simulations experiments showed concrete evidence of effectiveness with our proposed 3D directional sensing model and target the coverage algorithm in terms of solution precision and stability.

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