Full-View Barrier Coverage with Rotatable Camera Sensors

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***Abstract*—Camera sensors can collect visual information from regions of interest (RoI) and provide more information to classify the intruder. In practice, randomly deployed camera sensors can not guarantee that the barrier is full-view covered, and lead to a waste of sensing resources. Our work takes the first attempt to explore the deployment strategy to achieve full-view barrier coverage with rotatable camera sensors. We propose a method to select camera sensors from an existing and arbitrary deployment and determine their orientation to obtain a full-view barrier coverage. Our simulation results demonstrate that our algorithm outperforms existing algorithms for fixed directional camera sensors in saving the number of camera sensors.**

I. INTRODUCTION

Barrier coverage is an important model of coverage for various sensor network applications, e.g., national border control, critical resource protection, etc. A barrier sensor network is formed by a set of sensors whose sensing ranges are contiguous and span across the monitored field [1], and guarantees that every movement that attempts to cross from one side of a region to the opposite side will be detected in real-time with high accuracy and minimal manual intervention.

Unlike scalar sensors such as vibration sensors, camera sensors can collect visual information from the region of interest (RoI) and provide more information to classify the intruder and reduce false alarms [2]. With the emergence of cheap and compact camera sensors, it is becoming feasible to deploy a network of camera sensors working in concert.

However, the barrier coverage of camera sensors is much more complicated than the traditional barrier coverage problem. First, unlike an omnidirectional sensor, the sensing range of a camera sensor is usually modeled as a sector with a limited field of view. Therefore, the traditional solutions [3], [4] do not work in this scene. What is more, the camera sensors may generate very different views of the same object if they are from different viewpoints. Taking this into account, Wang *et al.* proposed a novel model called full-view coverage [5]. Considering the concept of full-view coverage, the choices of deployment orientation is much more complicated, and the former works based on directional sensors [6] could not be used in the camera barrier coverage, making this problem much more tricky.

In practice, camera sensors are randomly deployed in a RoI, for example, dropped by airplanes, this is because some regions are inaccessible or for the reason of saving the human resource. Obviously, after initial random deployment of camera sensors with limited sensing angle, full-view barrier coverage can not be guaranteed by simply selecting cameras across the field and it may lead to a waste of sensing resources. One intuitive way is to deploy camera with rotating ability to improve the utilization of deployed cameras instead of leaving them idle. However, several challenges need to be overcome. Since we seek to form a barrier that is full-view covered, we have strict requirements for the working direction of the deployed cameras. Furthermore, the number of possible directions of deployed camera can be an exponential function of the number of nodes, hence it is not possible to use the brute method. What is more, since the sensing field of the camera is limited, when its orientation is selected, it can not surveil other subregions in its sensing range, that means we need to coordinate the working directions of the deployed sensor. Hence, it is significant to set up a proper working configuration of the camera sensors to form a barrier.

In this paper, we take the first attempt to explore deployment strategy to achieve full-view barrier coverage

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with rotatable camera sensors. We model the full-view barrier coverage problem with rotatable camera sensors as a graph and propose a method to select camera sensors and working orientation to form a full-view barrier. Our simulation demonstrates that our algorithm outperforms the existing algorithms based on static orientation deployment in terms of number of sensors.

II. RELATED WORK

The barrier coverage problem is firstly studied in [1], and barrier coverage with camera sensors is first introduced in [7]. Wang *et al.* propose a novel model called full-view coverage [5], and study the problem of constructing a camera barrier. Based on the definition of full-view coverage, the Minimum Camera Barrier Coverage Problem (MCBCP) in camera sensor networks is studied in [8]. In [9], the authors concentrate on the critical condition of full-view coverage under uniform deployment in the static and three different mobile random deployed camera sensor networks.

A directional sensor may be able to rotate to different working direction $\overrightarrow{f}$ to monitor different sector areas. The problem that how each sensor calculates its next new direction to obtain a better coverage is studied in [10]. Tao *et al.* investigate the problem of finding appropriate orientations of directional sensors such that they can provide strong barrier coverage [6].

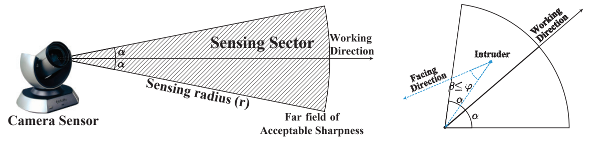
III. NOTATIONS AND MODEL

In this section, we introduce several terminologies on barrier coverage and present the sensing model for camera sensors.

We focus on a two-dimensional rectangular belt region, which is the boundary of the RoI. Usually, this region is generally a long and thin strip with the length of L and the width of W. To detect intruders that attempt to cross the deployed region into the protected areas, we randomly deploy stationary camera sensors which are assumed to have capability of knowing their location by GPS or a certain localization algorithm [11].

As shown in Fig.1(a), camera sensor is usually modeled as a directional sensor with an orientation $\overrightarrow{d}$ and a limited field of view. In optics, the depth of field (DoF) represents the portion of a scene that appears sharp in the image. Hence, far distance of acceptable sharpness of a lens can represent the sensing radius (r). The angular extent of a given scene that is imaged by a camera sensor is described by angle of view (AoV)-θ.The AoV in horizontal direction can be approximately computed by the formula $\theta = 2\alpha = 2\arctan\frac{d}{2f}$.

Therefore, the state of a camera sensor s_i can be represented by a 5-tuple $(x_i, y_i, r_i, \theta_i, \beta_i)$, where (x_i, y_i) is the two-dimensional location of the center of sensor s_i, r_i and θ_i is the sensing radius and angle of view, respectively. β_i is the orientation or the facing direction of s_i and $\beta_i \in [0, 2\pi)$. The sensing angle (θ_i) of directional sensors is usually less than π, and omnidirectional sensing model is a special case of directional sensing model when $\theta_i = 2\pi$.



(a) Sensing sector (b) Full-view Coverage

Fig. 1: Camera coverage model

For camera sensors, A point p is full-view covered [5] if for any facing direction (i.e., any vector $\overrightarrow{d}$), there is a sensor s_i, such that p is covered by s_i and $\angle(\overrightarrow{d}, \overrightarrow{ps_i}) \leq \varphi$, where $\varphi \in (0, \frac{\pi}{2}]$, is a predefined parameter which is called the effective angle (EA). A region $\mathcal{R}$ is full-view covered if every point in it is full-view covered.

Given a field $\mathcal{F}$ with one side being the entrance and the opposite side being the destination, a camera barrier $\mathcal{B}$ is a connected region inside $\mathcal{F}$ such that $\mathcal{B}$ is full-view covered and every path from one point on the entrance side to another point on the destination side intersects with $\mathcal{B}$.

IV. CAMERA COVERAGE DETECTION

In this section, we propose an efficient method to detect if the target barrier can be covered by a subset of deployed camera sensors. If such a barrier exists, our proposed method can select corresponding camera sensors from an existing deployment and determine their working directions.

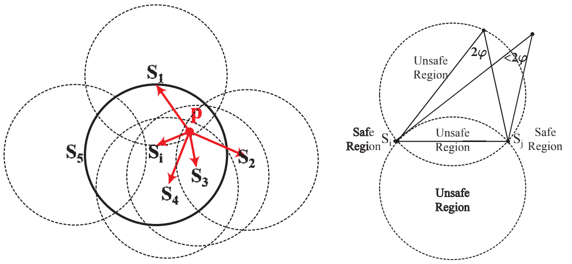
A. Method Overview

We get started with this problem by partitioning the RoI into small subregions according to the coverage. After subregion partition, we find out all possible full-view covered (FVC) subregion in the monitored field, and consider their connectivity and conflict caused by the limited sensing range of camera sensors. Based on the camera barrier graph, in Section IV-C we show that if we can find a path from the left boundary to the right boundary in the camera barrier graph, there exists a set of contiguous FVC sub-regions across the field, which is essentially the camera barrier we are looking for. We also utilize some redundancy reduction techniques to effectively reduce the number of cameras in use.

B. Camera Barrier Graph

The fundamental problem of our method is to find out the possible full-view coverage regions and decide their connectivity and conflict caused by the limited AoV.

1) Subregion Partition: For each camera sensor s_i, we say camera sensor s_x is a neighbour sensor of s_i if his distance from s_i is less than $r_i + r_x$, and the set of neighbour camera sensors of s_i are denoted by $\mathbb{N}_{s_i} = \{s_x | \|s_x s_i\| < r_i + r_x\}$. All the possible full-view coverage area covered by s_i must be covered by some other camera sensors from $\mathbb{N}_{s_i}$. Since the direction camera sensor s_i is not determined, all the possible directions form a disk area with radius r_i. The constrain of limited AoV will be considered in Section IV-B3. The sensing disks of each neighbour sensor $s_x \in \mathbb{N}_{s_i}$ partition the possible sensing disk of s_i into sub-regions as shown in Fig 2(a). By doing this for all camera sensors, we can partition the field $\mathcal{F}$ into small subregions, and then we determinate whether the subregion is full-view coverage in the next subsection.



(a) Subregion Partition & Coverage List (b) Full-view coverage region

Fig. 2: Coverage list

2) Full-view Coverage Determination: For a given region $\mathcal{R}$, suppose all points in $\mathcal{R}$ are covered by the same set of sensors $\mathbb{S}_{\mathcal{R}} = \{s_1, s_2, \cdots, s_m\}$. As shown in Fig. 2(a), we define a coverage list for any point $p \in \mathcal{R}$ regarding their face direction of $\mathcal{R}$ as follows. We begin with any vector $\overrightarrow{ps_i}$, then we rotate $\overrightarrow{ps_i}$ around p in the clockwise direction until it becomes parallel to the first direction $\overrightarrow{ps_i}$, all vectors met in the rotation construct the coverage list according to the rotation order, and the coverage list is denoted by $\mathbb{C}_p = \{\overrightarrow{ps_{i_1}}, \overrightarrow{ps_{i_2}}, \cdots, \overrightarrow{ps_{i_m}}\}$. The following lemma filters out non-FVC subregions of a camera sensor.

Lemma 1 (**Full-view Coverage Point** [12])**.** *A given point p is full-view covered if and only if the angle between any adjacent directions in $\mathbb{C}_p$ is less than or equal to 2φ, namely for $\forall\ \overrightarrow{ps_k}, \overrightarrow{ps_{k+1}} \in \mathbb{C}_p$, $\angle(\overrightarrow{ps_k}, \overrightarrow{ps_{k+1}}) \leq 2\varphi$.*

According to Lemma 1, a subregion $\mathcal{R}$ at least be covered by $\lceil \frac{\pi}{\varphi} \rceil$ camera sensors, namely $\|\mathbb{S}_{\mathcal{R}}\| \geq \lceil \frac{\pi}{\varphi} \rceil$, if it is full-view covered. So we can filter out sub-regions covered by less than $\lceil \frac{\pi}{\varphi} \rceil$ camera sensors, and verify the full-view coverage character of the rest sub-regions to find out all the possible full-view coverage area.

As shown in [5], the number of coverage sensors is not enough to recognize a full-view coverage region and we need to further define the safe region and the unsafe region of any two sensors as shown in Fig. 2(b). For any two sensors s_i and s_j, the safe region $\Omega(s_i, s_j)$ is the area in which for any point p, $\angle(\overrightarrow{ps_i}, \overrightarrow{ps_j}) \leq 2\varphi$; the unsafe region $\overline{\Omega}(s_i, s_j)$ is the area in which for any point p, $\angle(\overrightarrow{ps_i}, \overrightarrow{ps_j}) > 2\varphi$.

Now we have the critical conditions to find FVC regions.

Theorem 1 (**Full-view Coverage Region**)**.** *Supposing that each point $p \in \mathcal{R}$ have the same coverage list $\mathbb{C}_p = \{\overrightarrow{ps_{i_1}}, \overrightarrow{ps_{i_2}}, \cdots, \overrightarrow{ps_{i_m}}\}$, the region $\mathcal{R}$ is full-view covered by a sensor set $\mathbb{S} = \{s_{i_1}, s_{i_2}, \cdots, s_{i_m}\}$ if and only if*

- *$\mathcal{R}$ is within the polygon bound by $\{\overline{s_k s_{k+1}}, 1 \leq k \leq m\}$,*
- *The region $\mathcal{R}$ is covered by the sensing area of all camera sensor $s \in \mathbb{S}$,*
- *The unsafe region of s_k and s_{k+1} does not intersect with $\mathcal{R}$, where $1 \leq k \leq m$ and s_{m+1} denotes s_1.*

Based on the Lemma 1 and Theorem 1, we show how to find all the possible full-view coverage subregion of a camera sensor s. We firstly filter out subregions covered by less than $\lceil \frac{\pi}{\varphi} \rceil$ camera sensors as potential subregions. For each potential subregion $\mathcal{R}$, we eliminate the region with its intersection with the unsafe region of its coverage sensors $\mathbb{S}_{\mathcal{R}}$. If the rest of the potential subregion $\mathcal{R}'$ is not empty, then it is a FVC subregion. Otherwise, it is a non-FVC subregion.

There is one more issue that if a subregion is a FVC subregion, it may have more than one choice on the selections of the camera sensors. Since the number of coverage camera sensors may not be too much, we enumerate all possible selection the camera sensors and consider each FVC subregion $\mathcal{R}$ with its coverage camera sensors $\mathbb{C}_{\mathcal{R}}$ in the later discussion.

3) Conflict Determination: There may exist several FVC subregions in the coverage range of a camera sensor, however, it may be not able to cover all the FVC subregions because of the limited AoV. We consider this constrain in this subsection and give the concept of conflict subregions. For two full-view coverage region $\mathcal{R}_v$ and $\mathcal{R}_w$, they conflict to each other if there exists a camera sensor $s_i \in \mathbb{C}_{\mathcal{R}_v} \cap \mathbb{C}_{\mathcal{R}_w}$ can not cover the two area at the same time.

Firstly, a subregion we get through the former partition may not be totally covered by the corresponding working state. Thus we need to partition the subregion into some much more smaller subregions.

Furthermore, we note that for a camera sensor $s_i \in \mathbb{C}_{\mathcal{R}_v} \cap \mathbb{C}_{\mathcal{R}_w}$, where $\mathcal{R}_v$ and $\mathcal{R}_w$ are two full-view coverage region, the possible coverage may be one of the following three cases.

- There exists a working state that can cover the full region $\mathcal{R}_v$ and $\mathcal{R}_w$ at the same time.
- There exists a working state that cover the full region of $\mathcal{R}_v$ or $\mathcal{R}_w$, and a part of the other subregion.
- There is no working state can cover $\mathcal{R}_v$ and $\mathcal{R}_w$ at the same time.

In the first case, the $\mathcal{R}_v$ and $\mathcal{R}_w$ are not in conflict with each other, and $\mathcal{R}_v$ and $\mathcal{R}_w$ are conflict in the third case. However, in the second case we can not easily determinate where $\mathcal{R}_v$ and $\mathcal{R}_w$ are conflict to each other. Supposing s_i can only cover the full region of $\mathcal{R}_v$ and part of $\mathcal{R}_w$ which is denoted by $\mathcal{R}_{w1}$, we know the remain part of $\mathcal{R}_{w1}$, namely $\mathcal{R}_{w2} = \mathcal{R}_w - \mathcal{R}_{w1}$, is conflict with both $\mathcal{R}_v$ and $\mathcal{R}_{w1}$. Similarly, we can partition $\mathcal{R}_v$ into two subregions $\mathcal{R}_{v1}$ and $\mathcal{R}_{v2}$. We know that $\mathcal{R}_{w2}$ is conflict with $\mathcal{R}_{v1}$, $\mathcal{R}_{v2}$ and $\mathcal{R}_{w1}$, and $\mathcal{R}_{v2}$ is conflict with $\mathcal{R}_{w1}$, $\mathcal{R}_{w2}$ and $\mathcal{R}_{v1}$.

Now we can decide all the possible conflict relation between subregions.

4) Graph Construction: Based on the analysis shown before, we define the camera barrier graph to model the full-view barrier coverage problem with camera sensors.

Definition 1 (**Camera Barrier Graph**). *$\mathcal{G} \equiv (\{s,t\} \cup \mathbb{V}, \mathbb{E}_{\mathcal{N}} \cup \mathbb{E}_{\mathcal{C}})$ denotes the camera barrier graph, $\{s,t\} \cup \mathbb{V}$ and $\mathbb{E}_{\mathcal{N}} \cup \mathbb{E}_{\mathcal{C}}$ respectively represents vertex set and edge set. Vertex s, t denotes the left bound and right bound, respectively, and each vertex $v \in \mathbb{V}$ represents a full-view coverage area. A edge $e = (v, w) \in \mathbb{E}_{\mathcal{N}}$ if two full-view coverage area v and w are adjacent to each other. Edge $(s, v)(or(w, t)) \in \mathbb{E}_{\mathcal{N}}$ if the region vertex v represents can cover the left(or right) boundary. An edge $e' = (v, w) \in \mathbb{E}_{\mathcal{C}}$ if the working state of full-view coverage area v and w conflict with each other.*

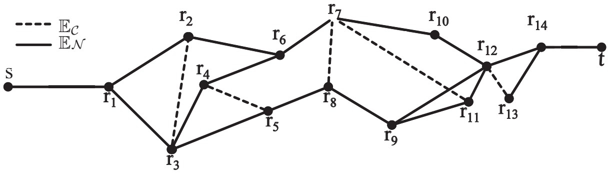


Fig. 3: Camera Graph

C. Camera Selection For Full-view Barrier Coverage

We know that if there exist a path composed of edges in $\mathbb{E}_{\mathcal{N}}$ from source s to the sink t and there are no two vertex in the path linked by edge in $\mathbb{E}_{\mathcal{C}}$, the subregions that vertices in such a path represent are connected and are not conflict to each other, name a camera barrier from the left boundary to the right boundary exists. Our problem is converted into finding such a path in the camera barrier graph. We give an algorithm which originates form Dijkstra algorithm in order to find a full-view barrier coverage form the left bound to the right bound. Algorithm 1 shows our idea in pseudocode.

Algorithm 1: Camera Selection For Barrier Coverage

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Input: The camera barrier graph $\mathcal{G} = (\{s,t\} \cup \mathbb{V}, \mathbb{E}_{\mathcal{N}} \cup \mathbb{E}_{\mathcal{C}})$.
Output: A path $\overrightarrow{\mathbb{P}}_t$ from source $s$ to the sink $t$.
$\delta(s) \leftarrow 0$;
Each $v \in \{t\} \cup \mathbb{V}$, $\delta(v) \leftarrow \infty$;
$\overrightarrow{\mathbb{P}}_t \leftarrow \varnothing, \mathbb{D} \leftarrow \varnothing, \mathbb{C} \leftarrow \{s\}$;
while $\|\mathbb{C}\| \geq 0$ do
    $c \leftarrow argmin_{v \in \mathbb{C}}\ \delta(v)$;
    foreach $w \in \mathbb{N}_c$ do
        if $\exists x \in \overrightarrow{\mathbb{P}}_w,\ (x, w) \in \mathbb{E}_{\mathcal{C}}$ then continue;
        if $w \notin \mathbb{C}$ or $\delta(w) > 1 + \delta(c)$ then
            $\delta(w) \leftarrow 1 + \delta(c)$;
            $\mathbb{C} \leftarrow \mathbb{C} \cup \{w\}$;
            $\overrightarrow{\mathbb{P}}_w \leftarrow \overrightarrow{\mathbb{P}}_c \cup (c)$;
        end
    end
    $\mathbb{D} \leftarrow \mathbb{D} \cup \{c\}, \mathbb{C} \leftarrow \mathbb{C}/\{c\}$;
end
return $\overrightarrow{\mathbb{P}}_t$;
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V. EVALUATION

In this section, we show simulation results on full-view barrier coverage problem.

A. Methodology

For the comparison with [8], we select the same scenarios that the RoI is a $10m \times 20m$ rectangle region. The cameras parameters are the sensing radius $r = 3m$, the AoV $\theta = \frac{\pi}{3}$ and the effective angle $\varphi = \frac{2\pi}{3}$. Cameras are deployed randomly and uniformly in the deployed field. To avoid the boundary effect[1], the deployed field is a larger area with both the length and the width r longer than the RoI. For each simulation setting, we calculate the results averaged over 1000 rounds.

B. Comparison with Static Direction Deployment

In [8], Ma *et al.* shows the result of a comparison of camera barrier coverage (CBC) and full coverage (FC) in a $10m \times 20m$ rectangle region. However, their camera sensors are deployed with static working direction, which may lead to a waste of sensing cameras when considering full-view coverage. As demonstrated in Fig. 5(a), the number of rotatable cameras required by barrier coverage (RCBC) is much less than that of minimum number of static deployed cameras. We also change the length of the field from $10m$ to $55m$ and

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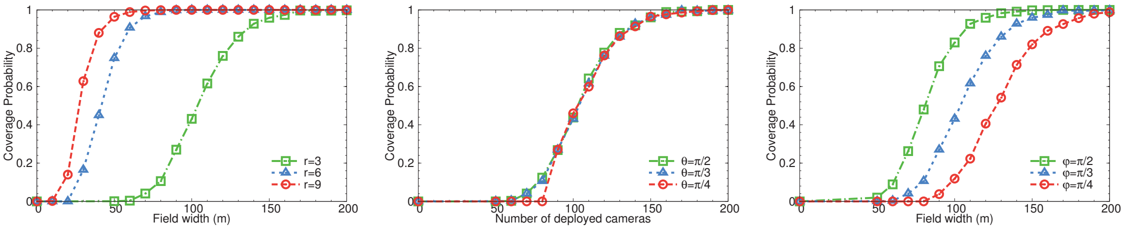
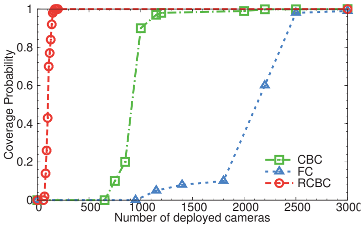
[1] If the deployment field is the same as the monitored field and the deployment is random and uniform, then the point close to the boundary is less likely to be covered than the point in the center area.



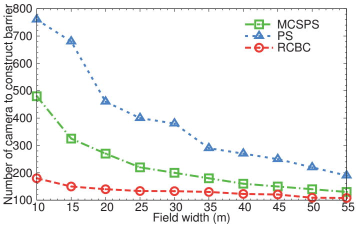
(a) Impact of sensing radius (r) (b) Impact of angle of view (θ) (c) Impact of effective angle (φ)

Fig. 4: Impact of camera parameters

observe how many cameras are needed to achieve the barrier coverage with at least 0.99 probability, when the cameras parameters and the width of the monitored field are fixed as in the above. As shown in Fig. 5(b), the number of cameras required for barrier coverage is much less than the number produced by Minimum Camera Sensors Path Selection (MCSPS) [8] algorithm and Shortest Path (SP) [12] algorithm. As the field width increases, the number of cameras required for full coverage reduces for the reason as shown in [8].



(a) Coverage probability vs. Number of cameras



(b) Impact of region of interest (RoI)

Fig. 5: Comparison with static direction deployment

C. Impact of Camera Parameters

We study the impact of the three camera parameters: the sensing radius, the AoV and the effective angle on the probability of camera barrier coverage. It is shown in Fig. 4(a) that larger sensing radius leads to less cameras needed to form a full-view barrier coverage, and this is consistent with our intuitions. In Fig. 4(b), it is seem that the AoV does not effect the number of cameras needed to form a full-view barrier coverage, that is because in that case, the field is partitioned to small subregions, camera sensor usually serves only one subregion and the other view is not utilized for the lack of FVC for other camera sensors. Intuitively, smaller φ implies more cameras required for an object to be full-view covered, and hence more cameras needed for a camera barrier, this is exactly Fig 4(c) shows.

VI. CONCLUSIONS

In this paper, we modeled the full-view barrier coverage problem with rotatable camera sensors as a graph and propose an efficient method to detect if the target barrier can be covered by a subset of deployed camera sensors. If such a barrier exists, we can select corresponding camera sensors and their working directions. This is the the first attempt to explore deployment strategy to achieve full-view barrier coverage with rotatable camera sensors. Our simulation results demonstrate that our algorithm outperforms the existing algorithm in terms of the number of camera sensors.

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