Abstract—Coverage is one of the most important issues in wireless visual sensor networks. In this topic, most efforts have been concentrated on two-dimensional plane coverage. While in some applications such as automatic surveillance, target tracking and target localization, the main interest is to cover 3D regions. However, these simplified plane coverage models cannot accurately characterize the actual 3D situations. To address this shortcoming, we define the concept of volumetric coverage, which considers three-dimensional instead of plane coverage. Also to preserve the volumetric coverage, a greedy camera selection algorithm based on multi plane coverage is presented. In this algorithm, cameras are selected as active via selection criteria which assigns priorities to cameras. In order to prolong network’s lifetime, minimum number of cameras are selected and also the remaining energy and the transmission cost of each camera sensor node are considered by selection criteria. Through simulations, the differences between plane and volumetric coverage models are illustrated and also the performance of our proposed method is proved.

Keywords— visual sensor network; volumetric coverage; greedy selection; multi plane coverage.

I. INTRODUCTION

In recent years, sensor networks have been among the topics of interest for the researchers. These networks consist of electronic devices with limited energy that have the capability of sensing the environment, processing the sensed data and communicating with each other in a wireless manner. In traditional wireless sensor network (WSN), sensors collect scalar data, such as humidity, temperature, pressure and seismic variations. Recent advances in the technology of low power camera manufacturing have caused these cameras to be used in sensor networks. Wireless visual sensor networks (WVSNs) are kind of ad-hoc networks that employ autonomous wireless sensors equipped with low-power cameras to collect visual information from a monitored field. Some of the important applications of WVSNs include environmental monitoring, wildlife observation, automated assistance for the elderly and disabled people, person location service and tracking of moving targets [1].

In these networks, coverage is one of the fundamental problems that directly impact on final quality of the application. In fact, for many applications of WVSNs, how well a monitored field is covered, is a crucial concern and should be properly answered. The importance of this problem varies depending on the application. For example in target tracking, this issue is more important than applications such as weather monitoring which are concerned with the sensing of large areas. In the coverage issue, how the monitored field is sensed with wireless nodes and how the redundant nodes can be used to prolong the network’s lifetime, should be considered. Also the quality of coverage and node connectivity is important [1].

Most of coverage algorithms in WSNs are not completely true for WVSNs. This is because the visual sensor model is directional, which differs from the omnidirectional model of the scalar sensors. Typically, the field of view (FOV) of a visual sensor is simplified as 2D sensing model. In such scenario, visual sensors are placed on a plane (sensor plane) and their coverage at a parallel plane is investigated. This model is used in [2] where it is assumed that sensors have the capability to change orientation after deployment. The goal of [2] is to find the orientation of the cameras which maximizes plane coverage. In [3] the weighted coverage problem is considered which assign priorities to different regions based on their importance. Then, the weighted coverage is preserved via genetic algorithm. In [4] wireless multimedia sensor networks have been studied which collect both acoustic and visual information. In such networks sensing model is hybrid and the goal is to find the number of sensors which should be deployed to guarantee that each point in the monitored environment is covered by multiple types of sensors. Theory of the virtual centripetal force is used in [5] to detect redundant nodes. Their objective has been to maximize the coverage by choosing best orientation of sensors and decreasing the overlap regions of sensor nodes. In [6], the area coverage via directional sensors with ability to rotate their angles has been addressed. In that paper, Voronoi diagram has been utilized to maximize the area coverage with minimum number of sensors. In order to obtain general information of the directional sensors, the traditional sensors with circular sensing model is used.

Soro et al. [7] have considered the differences between the video-based sensor networks and the traditional WSNs. They showed that WSN coverage algorithms are not efficient in the video-based sensor networks due to the directional camera sensing model. They mentioned the three-dimensional coverage space, but to simplify the problem, two-dimensional, or plane, coverage was considered. They assumed that visual sensors are placed on a plane and cameras can capture images
from a monitored parallel field. Authors of [8] define 3D
directional sensing model for cameras and address the coverage
enhancement with adjustable 3D orientation, and for
simplicity, the monitored scene is considered as a 2D plane.
They used Simulated Annealing algorithm for optimization. In
[9] 3D sensing models in cameras with tuneable tilt and
deviation angle are utilized. In that work, the tilt angle is
adjusted to maximize the coverage area via changing the
sensing direction, then particle swarm optimization (PSO) is
used for deviation angle alteration to eliminate the overlapped
area and blind spots.

Existing coverage algorithms focus on providing coverage
in 2-D plane, because of the complexity of the volumetric
coverage design and analysis [10]. This simplification is not
tolerable in most cases and does not accurately characterize the
actual situation. Also accurate monitoring needs algorithms
which guarantee full volumetric or three-dimensional coverage.
We see that in none of the current algorithms, volumetric
coverage has been considered. The aim of volumetric coverage
is to observe each points of 3D monitoring region at least by
one sensor. Hence, in this paper we address this problem. We
proposed the multi plane volumetric coverage algorithm. In
this algorithm, sensors for coverage of several planes are
selected and volumetric coverage is estimated by these
cameras. The differences of volumetric and plane coverage are
illustrated in Fig. 1.

The rest of the paper is organized as follows. In section 2
the network model, the sensing model and the network’s
properties are described. The proposed algorithm is explained
in section 3. In section 4 simulation results of the proposed
algorithm are presented and section 5 concludes the paper.

Figure 1. Cross section of distributed sensors on ground, plane coverage at
height Hm, and volumetric coverage between Hm and Hk.

II. SENSING MODEL AND NETWORK PROPERTIES

In this section, sensing model of cameras, some essential
definitions and the network’s properties are presented.

A. Sensing Model

In WVVSNs, communication neighbors of sensors differ
from their sensing neighbors, since cameras have directional
sensing direction [11]. Hence, in these networks two types of
sets can be defined.

Definition 1: Sensing neighbor set is the set of sensors which
have overlapped field of view (FOV) with sensor $S_i$. The
sensing neighbors of $S_i$ is hence defined as:

$$N_s(S_i) = \{S_j \in N \mid \text{FOV}_{S_i} \cap \text{FOV}_{S_j} \neq \emptyset\}$$

(1)

Definition 2: Communication neighbor set is the set of sensors
which are in communicational range of the sensor $S_i$. Hence,
the communication neighbors of $S_i$ are defined as:

$$N_c(S_i) = \{S_j \in N \mid d(S_i, S_j) \leq R\}$$

(2)

where $N$ denotes the set of all sensors in the network. Also,
distance $d(S_i, S_j)$ is the Euclidean distance between sensor $S_i$ and $S_j$
while $R$ is the communication range of this sensor.

According to the above definitions, visual sensor networks
are modelled by using two undirected graphs: communication
graph, which represents the communication between nodes,
and the vision graph that represents the visual relationships
between the cameras.

Vision graph: Based on definition 1, undirected weighted
graph $G_v$ is constructed. In this graph, a sensor is represented
as a vertex and the sensing area of the sensor is used as the weight
of that node, $W_{vi}$. Each sensor is connected to sensors which
are in its $N_v$. The amount of overlapped regions between two
connected sensors ($S_i$ and $S_j$) are used as the weights
of the edge, $W_{ij}$.

Communication graph: in the communication graph $G_c$,
sensors are represented as vertices and each sensor is connected
to sensors which are in its $N_c$ set.

B. Network Properties

In this paper, we consider a set of $N$ cameras uniformly
distributed on a plane such that they monitor the space above
them. Pinhole camera model is considered and each camera
node in the network is represented by a six-
tuple $(x_i, y_i, z_i, \theta_i, \phi_i, \psi_i)$. In this six-tuple, $(x_i, y_i, z_i)$ defines
the sensor’s position on the sensor plane and $(\theta_i, \phi_i, \psi_i)$ are the
rotation angles of the sensor around the world coordinate axis.
These six parameters are the sensor’s parameters and are
obtained via a calibration process.

In this paper, we consider a centralized algorithm which is
performed by sink node. After the calibration process, the
vision and communication graphs can be constructed using the
obtained sensor parameters. For the vision graph, the
monitored space is divided into equal cubes and the centres
of each cube are to be observed at the camera image plane. The
collection of these points determines the sensing region of each
camera. Constructing a vision graph in this way could be very
accurate but depending on the size of the monitored space and
the number of sensors, this could demand large computational
overhead. To overcome this overhead, the proposed algorithm
constructs the vision graph for only considered plane and each
plane divided to equal square instead of cube. The sensor
selection to guarantee full coverage is performed by the sink
node. Selected sensors will send the sensed information to the
sink node and the other nodes remain in sleep mode.
The applied routing algorithm is based on the ad hoc on demand distance vector (AODV) protocol and sensors select the shortest path to the sink node for sending information. After any change in the set of live sensors, the communication graph is updated.

In the followings, we present our proposed greedy plane coverage (GPC) and multi plane volumetric coverage (MPVoC) algorithms.

III. PROPOSED VOLUMETRIC COVERAGE ALGORITHM

When sensors deployed randomly and without any predefined map on the sensor field, it generates regions with redundant sensors as well as regions with sensor sparsity. In such networks due to lack of exact information about nodes’ locations, redundant sensors are used for quality assurance [1]. These sensors are low power and have limited battery and processing power. Therefore, the amount of energy for prolong network lifetime should be considered in the sensor selection process. For the coverage issue, if the region be dense, most of the sensors may observe a common region. If sensors with minimum overlapped regions are selected, redundant nodes could be used to prolong the network’s lifetime. The camera selection problem to cover all points of the 3D field can be solved with a greedy approach where at each step sensors are selected with maximum coverage and minimum overlap with the previously selected sensors. The coverage of this 3D region has heavy computational overhead. Therefore we present an algorithm which considers multi plane coverage to provide volumetric coverage. In the proposed algorithm, the 3D monitoring region is divided to multiple planes and coverage of these planes is investigated. The number of these planes is related to the desired accuracy. To obtain coverage of each plane, the greedy plane coverage (GPC) algorithm is presented which selects cameras according to their priority. In order to attain volumetric coverage, an algorithm is proposed to incorporate this multiple plane coverage.

A. Greedy Plane Coverage Algorithm

In order to select cameras to cover the plane, we proposed the criterion of selecting sensors which have higher priorities. In this criterion, sensors with higher coverage and lower overlap improve the coverage rate and are of higher interest than others. Also sensors with higher remaining energy cause prolongation of the network’s life time and are more desirable. Moreover, a selected sensor for sensing the environment, consumes energy for sending the collected information to the sink node; hence, it is better to select sensors with minimum transmission cost. We define a priority value for each sensor and consider four parameters. These parameters are coverage rate, remaining energy, transmission cost and the amount of overlap area between sensors. This priority value is directly related to the coverage ratio and the remaining energy and inversely related to the transmission cost and the overlap area. In Equation (3) we formulated the priority of a sensor $S_i$.

$$\text{Priority}(S_i) = \alpha \cdot \frac{C_R(S_i)}{OVL(P(S_i,C_z))} + \beta \cdot \frac{E_R(S_i)}{C_T(S_i)}$$  \hspace{1cm} (3)

where $C_R$ denotes the coverage rate, $E_R$ is the remaining energy and $C_T$ is the transmission cost from $S_i$ to sink node. Also, $\alpha$ and $\beta$ are the importance factors of the parameters. Furthermore, $OVL(P(S_i,C_z))$ indicates the amount of overlapped area between $S_i$ and the selected cameras, $C_z$ which is defined as Equation (4).

$$OVL(P(S_i,C_z)) = \begin{cases} 1 & \text{FOV}(S_i) \cap \bigcup_{j \in C_z} \text{FOV}(S_j) = \emptyset \\ \text{FOV}(S_i) \cap \bigcup_{j \in C_z} \text{FOV}(S_j) & \text{otherwise} \end{cases}$$  \hspace{1cm} (4)

where $\text{FOV}(S_i)$ denotes the field of view of sensor $S_i$. In this equation, if the new selected camera has no overlap with the other cameras which are selected, the $OVL(P(S_i,C_z))$ is considered as 1.

In the plane coverage algorithm, priorities of all cameras are computed according to Equation 3. Then cameras with higher priorities are selected until the coverage ratio does not increase and becomes constant. The pseudocode of the greedy plane coverage algorithm is illustrated in Fig. 2.

Algorithm : Greedy Plane Coverage

Inputs: $S$: set of camera, $H_z$: coverage plane.

BEGIN:
01. $C_R = 0$; // $C_R$ is coverage ratio of selected camera
02. $\text{Selected}_{\text{camera}} = 0$; // Set of selected camera
03. REPEAT
04. Calculate $P_{S_i}$. Priority of each sensor
05. $C_{R_{\text{old}}} = C_R$;
06. add $S_i$ with maximum $P_{S_i}$ from $S$ to $\text{Selected}_{\text{camera}}$
07. Calculate $C_R$ for sensors in $\text{Selected}_{\text{camera}}$
08. UNTIL $C_R = C_{R_{\text{old}}}$
END

Output: Selected camera

Figure 1. Pseudocode of proposed GPC algorithm.

B. Multi Plane Volumetric Coverage

To preserve the volumetric coverage, multi plane coverage is proposed. The monitored area is divided into a number of planes parallel with the camera distribution plane. Then sensors are selected for coverage of each of these mentioned parallel planes using GPC algorithm.

Suppose the monitoring field is divided to $k$ plane at different heights, such that $H_{\text{min}} = H_1$, $H_2$, ..., $H_k = H_{\text{max}}$. At first step, the coverage of plane $z = H_k$ is acquired via GPC, and then the coverage ratio of the plane $z = H_{k-1}$ are computed by the selected cameras. If the coverage ratio of this plane is less than desired coverage rate the GPC algorithm is applied to cover the $z = H_{k-1}$ plane, otherwise the coverage of another plane is considered. This process is continued for all $k$ planes. The set of selected cameras from $k$ plane-coverage cases are used to estimate the volumetric coverage. These cameras remain unchanged as long as all sensors have enough energy for processing and transmission of data. As soon as one sensor’s energy is finished, the sink node removes the sensor
from the graphs and updates the transmission path and transmission cost for those sensors that were transmitting data through the removed sensor. This process is continued as long as there are number of cameras with acceptable amount of energy. The pseudo code of this algorithm is illustrated in Fig. 3.

**Algorithm : Multi Plane Volumetric Coverage**

**Inputs:** $k$: number of planes, $\tau$: Maximum Coverage Ratio, $G_c$: Communication graph, $G_v$: vision graph, $S$: Set of Camera, $E_R$: Remaining Energy, $E_F$: Processing Energy.

**BEGIN:**

1. $C_k = 0; // coverage ratio$
2. $Selected\_camera = \Phi; // Set of selected camera$
3. $Selected\_camera = GPC(S, H_k) \cap H_k$ is $k^{th}$ plane
4. **REPEAT**
5. **FOR** $i=k+1$
6. $Calculate C_k$ for sensors in $Selected\_camera$
7. **IF**($C_k < \tau$)
8. $Selected\_camera = Selected\_camera \cup GPC(S, H_i)$
9. **END IF**
10. **END FOR**
11. **REPEAT**
12. **UNTIL** ($E_R(S)_{Selected\_camera} > E_R(S)_{Selected\_camera}$)
13. *remove $S_j$ from $S$; update $G_c$, $G_v$*
14. **UNTIL** $Selected\_camera \neq \Phi$

**END**

Figure 2. Pseudo code of proposed MPVoC algorithm.

IV. EXPERIMENTAL RESULT

In this section, we present a set of experiments to evaluate the performance of our proposed MPVoC algorithm. To evaluate it, we implemented our method in MATLAB environment. In each simulation run, we randomly distribute 50 camera sensor nodes using a uniform distribution. The rotation angles $\theta_i, \phi_i$ are randomly selected between zero and $\pi$ and $\phi_i$ with respect to $z$ axis is between zero and $2\pi$. In these simulations, the monitoring field is 40x40x100 area and the camera sensor nodes are distributed on plane $z = 0$. The goal of our simulations is to cover the monitoring field from height $H_{min} = 0$ to $H_{max} = 100$.

We compare the proposed algorithm with a volumetric greedy selection (VGS) algorithm. The VGS uses the same method as GPC, but the priority values for all sensors are computed by considering the vision graph for all monitoring area instead of specified planes. In such case, the computational overhead for computing the vision graph for all volume of monitoring area is increased.

To show the importance of the volumetric coverage, we compare the volumetric coverage with the plane coverage. In previous works, volumetric coverage has been estimated with plane coverage but simulations show that this estimation is not accurate. In our simulations we consider plane coverage at different height and select sensors with GPC algorithm to maximize the coverage at these planes. Then based on the selected sensors the volumetric coverage ratio from $H_{min} = 0$ to $H_{max} = 100$ and the plane coverage ratios are computed. Fig. 4 illustrates the difference between the plane and volumetric coverage ratios. This difference shows that the selected sensors for the plane coverage are not sufficient for the volumetric coverage. Applications for which high accuracy and high coverage ratio are essential, this difference cannot be ignored. Also this figure shows the effect of plane coverage at different height on volumetric coverage.

Fig. 5 compares the MPVoC algorithm with $k = 4$ and VGS approach. This figure illustrates that the estimation of volumetric coverage with multiple plane is closed to full volumetric coverage. Therefore, by considering the coverage of multiple planes instead of all 3D regions, the coverage rate can reach the maximum ratio of coverage with less time complexity.

The Fig. 6 shows the effect of different number of planes in MPVoC. As the number of planes increased, the coverage ratio is also increased and close to VGS algorithm, however the computational overhead is increased. Therefore, there are tradeoffs between the coverage rate and the complexity of the algorithm, and the number of planes can be chosen according to the requirement of the application.

In Fig. 7, differences between the plane coverage at $H = 100$ and volumetric coverage with different volumes are illustrated. The volumetric coverage from $H_{min} = 80$ to $H_{max} = 100$ is closer to plane coverage at $H = 100$ than any other volumetric coverage cases. Whenever the difference between the two planes is low, then the volumetric coverage can be estimated by the plane coverage. In future works we will involve elaborate routing algorithms [12] to calculate $C_{\tau}$.

V. CONCLUSION

In order to provide 3D coverage for a monitored region, we defined volumetric coverage for WVSNs and then we presented a multi plane coverage algorithm for selecting sensors for preservation of volumetric coverage. In the proposed algorithm, the monitoring area was divided into a number of planes which are parallel to the sensor plane, where the sensors are distributed. The integrated coverage of these planes was defined as volumetric coverage. Through large number of simulation, the difference between volumetric coverage and plane coverage was investigated. The importance of volumetric coverage was emphasized. Also, the tradeoffs between the coverage rate and the time complexity were emphasized. The number of planes can be chosen adaptively according to the required accuracy of the application. Also we showed that the volumetric coverage can be estimated by plane coverage if the height of the monitored filed is relatively low.

REFERENCES


Figure 4. Plane coverage vs. volumetric coverage.

Figure 5. VGS vs. MPVoC.

Figure 6. MPVoC with different number of plane.

Figure 7. Differences between volumetric and plane coverage ratios for different volumes.


