Efficient Camera Selection for Maximized Target Coverage in Underwater Acoustic Sensor Networks

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Abstract—**In addition to sensors, cameras have started to be deployed in underwater acoustic sensor networks (UWASNs) for improved monitoring. However, since cameras already consume a lot of energy, they are kept in sleep mode most of the time and only activated when sensors detect a target. Due to random deployment and lack of cameras, there may not be any cameras within the vicinity of a detected target. A possible solution to this problem is to relocate remote cameras via vertical movements to certain locations to capture the target. In this paper, we propose a distributed camera selection and relocation scheme in UWASNs to maximize the coverage of the detected targets with the least vertical movement of cameras. The problem is modeled as a weighted set covering problem and solved using a greedy heuristic. The performance of the proposed approach is assessed through extensive simulations under a variety of conditions.**

I. INTRODUCTION

Underwater Acoustic Sensor Networks (UWASNs) can consist of a large number of sensors on and underwater which can communicate via acoustic links [1]. Similar to terrestrial WSNs, these networks provide numerous advantages in terms of coverage quality, labor, cost and deployment as opposed to traditional underwater sensor networks. Within the last decade a lot of studies focused on the issues related to communication underwater given that RF signals would not travel underwater. The design of acoustic modem, modeling of the channel, medium access, routing and sensing issues had been the main focus of researchers [1].

With the development of low-cost battery-operated underwater cameras, UWASNs can also be equipped with such cameras to do object tracking or identification via the image/video of the object detected [2]. These cameras can be used in many applications such as habitat monitoring as an alternative to sonar imaging devices which are much more expensive. However, since the processing and transmission of multimedia data is very energy consuming the cameras can be on sleep mode most of the time and used on demand [1]. For instance, an ultrasonic sensor [3] can detect a target and then actuate a camera to capture the target for a while. However, if there is not sufficient number of cameras nearby the target (due to random deployment), the target may not be captured. One possible solution to this problem is to move cameras close to the target if the cameras have the ability to do so (i.e., nodes can move in vertical direction by using pumps [4]).

In this paper, we study this problem of camera selection and movement in UWASNs for capturing the detected targets with the least camera count and movement. This problem is a novel problem that requires a lot of subproblems to be solved. First of all, the area to be covered by cameras need to be determined by considering the messages coming from acoustic sensors which detected the target. Second, the portion of the target that can be covered by a particular camera needs to be determined and shared with other cameras. Third, we also need to maintain the connectivity of the UWASN when a camera is moved. And finally, we need to find the minimum set of cameras that will be required to maximize the coverage of the target with the least camera overlap. Note that elimination of redundancies in 3-D is a challenging problem, especially, when it is studied under the camera frustum. While 2-D versions of this problem in terrestrial wireless camera networks have been studied [5], to the best of our knowledge, this 3-D version with vertical movement of cameras has not been studied before.

We propose an approach that can coordinate the movement of appropriate cameras through the on-surface gateway. Each camera provides its location and orientation information to the gateway in advance so that the gateway can process this information in real-time when a request comes from the sensors to actuate cameras. When a target is detected, an approximate bounding box which contains the target is computed. The gateway then runs an algorithm to determine the cameras that are qualified to be cover the bounding box by vertical movement. Specifically, for each camera the gateway determines the set of discrete points it can cover with the least vertical movement. This problem is similar to minimum set cover where the discrete points for the bounding box constitute the set to be covered by the subsets owned by each camera. We model the problem as a weighted minimum set cover to also accommodate the distances of cameras to the target. Since weighted minimum set cover is also an NP-hard problem, we used a greedy heuristic for faster processing.

We implemented this approach in a simulated environment and assessed its performance in terms of various metrics such as movement distance, coverage and process completion time. The approach is also compared to a theoretical baseline where the cameras can be selected and moved from any location in the network (i.e., trying all the available cameras).

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II. RELATED WORK

The use of cameras in underwater environment have recently been introduced in [6], [7]. While [6] focused on quality of service on image transmission in underwater environments, [7] investigated cross-layer solutions and error correction schemes that will improve the quality of underwater communications for delay-tolerant applications. None of them have looked at the camera coverage and actuation issues.

In [8], it has been shown that a polynomial time solution is available in 2-D environment for full coverage of the monitored region. In this problem, manual deployment of nodes is required since the topology of network globally has to be known in advance. This solution, however, can not be used in UWASNs where the nodes are uniform randomly deployed.

In [5], Newell et al., propose a low-cost distributed actuation scheme which provides necessary coverage by turning on the least number of cameras to avoid possible redundancy. In [9], the authors considered a set up where occlusions and cameras are randomly placed. The distributed algorithm adjusts the cameras orientation rather than actuating it. Different than the above works, we have a 3-D environment where camera coverage computation is a challenge. Identification of whether a point is covered or not requires excessive computations in 3-D. We propose representing the targeted region as a discrete set of points and identify the overlaps among the covered points not covered actual regions.

Moving the nodes vertically in UWASNs has been widely used in a lot of approaches in the past [4], [10]. While some of these approaches assumed tethered nodes whose depth can be controlled from the top, the others assumed water discharging/taking mechanisms to adjust the depth of the node in the water. We considered the former, as in the second one also needs to deal with the mobility of the nodes due to underwater effects.

III. SYSTEM MODEL AND PROBLEM DEFINITION

We assume a randomly deployed connected network in 3-D. The nodes can be deployed using the technique in [4] where the sensors are dropped to the water surface and their depth are adjusted for maximized coverage and guaranteed connectivity.

There are 2 different types nodes in the assumed network model: 1) Ultrasonic sensors [3], 2) Low-resolution cameras. Both sensors and cameras have the ability to adjust their depths by a winch-based mechanism proposed in [11].

In our model we assume the availability of ultrasonic sensors whose working principle is based on sending sound signal and waiting for echoes. The sensing range of a sensor is assumed to be a spherical region with radius s (which is similar to radar). In addition to sensors we used low-resolution underwater cameras. We assumed that each camera has a random orientation. We also assume that both sensors and cameras can know their 3-D locations via localization techniques underwater [12].

The 3-D model of a camera is shown in Fig. 1. The camera field-of-view (FoV) is identified by angles α and β as well as the camera frustum. The camera depth-of-Field (DoF) can be represented by d_1 and d_2.

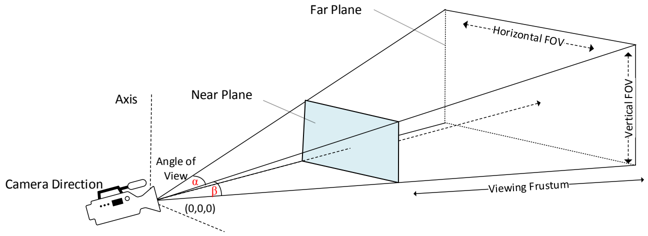


Fig. 1: Underwater Camera model.

A. Problem Definition

The problem is defined as follows: "Given a connected network of size s sensors and c cameras where $s >> c$ and a surface gateway, if there is a mobile target passing from the region, our goal is to detect it first with ultrasonic sensors and then get a video of this target to understand its category (i.e., a fish or submarine). Since the cameras are on sleep and not available everywhere in the region, our goal is to maximize the video coverage of the target with the minimized energy cost (the movement distance for the cameras) and delay by using a distributed approach."

IV. DISTRIBUTED SET COVER-BASED APPROACH

We address the challenges regarding what to cover (e.g., localizing the target area), which cameras are qualified to cover (e.g., determining the cameras that can wholly or partially covering the target area) and elimination of overlaps among the qualified cameras. The computations for overlaps are done in advance at the surface station and thus the cameras move only when the computations are finished. We explain these steps in details below.

A. Proactive Camera Identification and Localizing the Target

Since all of the computations for camera selection will be done by the surface gateway station, we follow a proactive approach and store all camera information in this gateway for future access. This will accelerate the process of camera selection and relocation since there will not be any need to search for the appropriate cameras.

When any of the sensors detect a target, they send a signal to the surface gateway which identifies the sensor ID and its location. The gateway aggregates these messages to locate the targeted area. Basically, the gateway uses the sensing sphere of each sensor and tries to find the union of these spheres to come up with a minimum bounding box since the target will definitely be in this box. Note that this bounding box is represented as a list of discrete points which will be tried to be covered by the cameras. We referred to it as **TargetSet** thereafter.

B. Coverage Computation for Each Camera

Once the target region to be covered is identified, then the gateway will refer to its camera list to select the cameras. For a camera, the possibility of covering any parts of the **TargetSet** depends on the location of the camera. If the X coordinate of a camera is smaller than starting X coordinate of **TargetSet** minus d_2, then we conclude that the camera cannot reach to any points in the **TargetSet** and therefore it is not selected.

For each camera, our proposed approach determines whether a given point **v = [x, y, z]** in **TargetSet** sits within the frustum of that camera.

As there is a list of discrete points for the **TargetSet**, the proposed algorithm checks these points one by one by considering different vertical locations (i.e., from 0 to MAX_{depth}) for a camera. This is done gradually by an incremental approach until the number of points to be covered are maximized. For each possible z value, we calculate how many points of **TargetSet** that camera would cover if the camera was there. Finally, we basically find the depth that maximizes how much of the **TargetSet** would they cover (see Fig. 2).

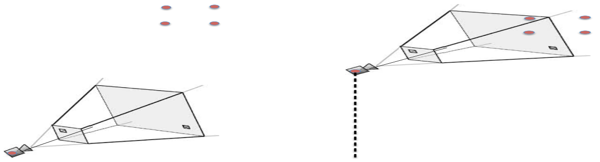


Fig. 2: Adjusting the depth of a camera to cover some points

C. Camera Selection to Minimize Overlaps

When the cameras are identified along with the points they can cover, then the problem is which cameras need to be picked to maximize the coverage of the **TargetSet**. Obviously, all of the cameras can be picked but there may be a lot of overlaps and eventually moving all the cameras would significantly increase the movement costs. On the other hand, if we try to minimize the number of cameras to be moved, then this may adversely affect the coverage ratio for the **TargetSet**. Therefore, we need a solution that will maximize our coverage while minimizing the camera count and overlaps.

We propose modeling this problem as a set covering problem. In a typical set covering problem, there is a number of given subsets and the goal is to cover the superset by selecting the minimum number of subsets. This problem is NP-Hard [13]. In our case, the subsets correspond to the point sets that are identified for each camera and we are trying to cover the **TargetSet** with the least cost movement of cameras. This does not necessarily indicate the minimum number of cameras since we also need to take into account the distances they will move. Therefore, for each camera picked, we need to assign a weight based on its movement cost. This transforms the problem to a new version called Weighted Minimum Set Cover [14]. One final issue is that in our case, there may not be a solution to this problem (i.e., we may not find cameras to cover all the points in **TargetSet**). Therefore, we change the problem to maximization of the coverage with the least cost.

Since an optimal solution to this problem would not be possible in polynomial time, we revised the greedy heuristic in [14]. In the greedy set cover problem: iteratively, we pick the most cost-effective set and remove the covered elements, until all elements are covered.

V. EXPERIMENTAL EVALUATION

A. Experiment Setup

The proposed approach is evaluated in simulated setting which consists of a three-dimensional rectangular monitoring area of size 10mx10mx50m. 15 random and connected topologies are created for each number of nodes and average of these topologies were reported. The number of cameras is assumed to be 20% of total number of nodes. The communication range for the nodes and the sensing range for acoustic sensors is assumed to be 100m and 30m respectively. The cameras are assumed to be moving vertically with a speed of 2.4m/sec [4]. The target is assumed to be randomly created in any location. The target can be represented as a set of discrete points.

The metrics to be evaluated in the experiment are **Coverage** (Camera coverage percentage for the target), **Movement cost** (Total vertical movement by the cameras), **Completion time** (Total time elapsed to complete the camera movement).

We compare the proposed approach to that of a theoretical approach where there is no restriction in terms of movement of the cameras. While this is not practical in practice, we use it as a benchmark to assess the performance of our approach.

B. Experiment Results

1) Movement Cost under a Variety of Coverage

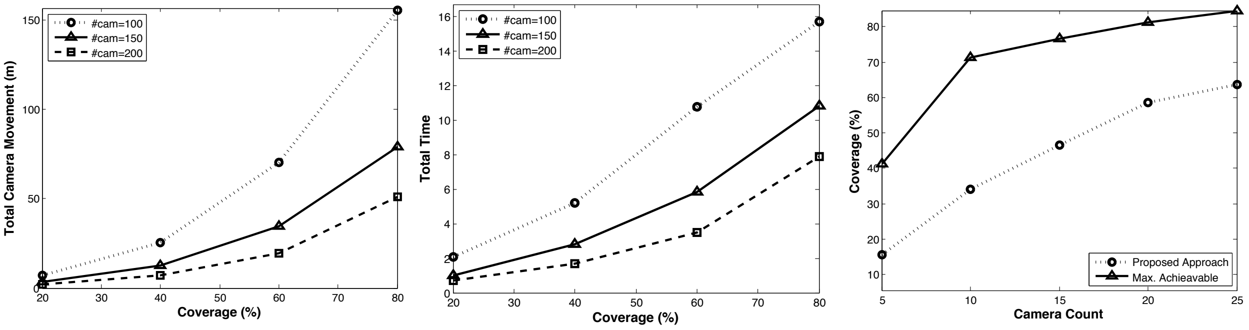
In the first experiment, we kept the number of nodes and cameras fixed and generated topologies where we achieved different coverage ratios. For each coverage percentage, we checked the total movement of cameras.

The results illustrated in Figure 3a indicate that the cost of camera movement increases as the coverage percentage increases. This is expected since moving the cameras which are in the close proximity of target may be enough to cover the target with a smaller percentage. On the other hand, if we want to cover the target with a larger percentage we may need to move some other cameras which are located far from the target. An interesting observation is that the increase in the coverage results in a non-linear increase in the camera movement. For instance, for achieving 80% of coverage, the camera movement costs are increased significantly.

Another observation is that if we employ large number of cameras, it is more likely to find an appropriate camera which covers some parts of the target and thus the total cost of movement will be less.

2) Completion Time under a Variety of Coverage

In the second experiment, we kept the same setup as above and checked the total completion time. The results shown in Figure 3b indicate that total time increases as the coverage percentage increases. Same reasoning can be applied to explain such an increase in the total completion time and thus the results are very similar to the one shown in Figure 3a. The time is dominated with the maximum movement distance for a scenario. In case of increased camera count, this distance can be reduced as there will be more camera options available. With the increased coverage requirement, it is likely that more



(a) (b) (c)

Fig. 3: (a) Total camera movement for varying coverage. (b) Total completion time for varying coverage. (c) Coverage percentage comparison for varying camera count

cameras will be moving and possibly from longer distances and thus the completion time increases.

3) *Coverage under a Variety of Camera Count: Maximum Achievable vs Our Approach*

In this part of simulations, we varied the number of cameras used and captured the percentage of coverage which was achieved by both our proposed approach and theoretical baseline approach. Such an unconstrained mobility of cameras provides a flexibility of finding an appropriate camera which can cover the target. In this way, we strived to assess the performance gap of our approach and identify the number of cameras needed to maximize the coverage. We represent this baseline approach as Maximum Achievable.

Fig. 3c indicates that the achievable coverage is much higher since the size of the candidate camera set is larger. The approach can find other cameras with different orientation and can cover more points. We would like to note that even in the case of the availability of more cameras, full coverage will not be achieved easily. However, as number of cameras increases the gap between the achievable maximum coverage and our proposed approach decreases. The reason can be attributed to the fact that if we employ more cameras the probability of finding an appropriate camera which can cover the target (partial or whole) by changing its depth increases. Therefore, the number of cameras need to be picked based on the application-level needs. If the target should be captured as a whole, then employing more cameras would make sense.

VI. CONCLUSION

We investigated the problem of camera actuation in UWASNs for efficient network operation. Once a target is detected using low-cost acoustic sensors, sleeping cameras can be activated to capture this target fully or partially. Since cameras can be randomly deployed, we proposed a solution that will identify the least number of cameras with the least-cost movement based on the location of the target. A surface gateway collects information from the sensors and cameras and determines the best cameras to move. We also modeled the problem of camera selection as a weighted minimum set cover problem and proposed a greedy heuristic. Compared to a baseline which has the ability to move all the cameras in the UWASN, our approach can provide very similar coverage performance. In addition we showed that there is an inherent tradeoff between the coverage ratio and the number of cameras available.

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