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Maximizing heterogeneous coverage in over and under provisioned visual sensor networks

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ABSTRACT

We address "heterogeneous coverage" in visual sensor networks where coverage requirements of some randomly deployed targets vary from target to target. The main objective is to maximize the coverage of all the targets to achieve their respective coverage requirement by activating minimal sensors. The problem can be viewed as an interesting variation of the classical Max-Min problem (i.e., Maximum Coverage with Minimum Sensors (MCMS)). Therefore, we study the existing Integer Linear Programming (ILP) formulation for single and k-coverage MCMS problem in the state-of-the-art and modify them to solve the heterogeneous coverage problem. We also propose a novel Integer Quadratic Programming (IQP) formulation that minimizes the Euclidean distance between the achieved and the required coverage vectors. Both ILP and IQP give exact solution when the problem is solvable but as they are non-scalable due to their computational complexity, we devise a Sensor Oriented Greedy Algorithm (SOGA) that approximates the formulations. For under-provisioned networks where there exist insufficient number of sensors to meet the coverage requirements, we propose prioritized IQP and reduced-variance IQP formulations to capture prioritized and group wise balanced coverage respectively. Moreover, we develop greedy heuristics to tackle under provisioned networks. Extensive evaluations based on simulation illustrate the efficiency and efficacy of the proposed formulations and heuristics under various network settings. Additionally, we compare our methodologies and algorithm with two state-of-the-art algorithms available for target coverage and show that our methodologies and algorithm substantially outperform both the algorithms.

1. Introduction

A visual sensor network (VSN) consists of a large number of visual sensors having local image processing, communication, and storage capabilities that monitor a set of targets within an area of interest. The sensors–also known as *smart cameras*–are capable of self-controlling their orientation and range based on environmental conditions. Visual Sensor Networks have received appreciable attention of researchers due to their applicability in a wide number of significant real-life scenarios.

Visual sensors can be either omni-directional or directional. A sensor can provide coverage to a target if the target is within the sensing region of the sensor. Omni-directional visual sensors can provide coverage to all targets placed within its sensing region at the same time, whereas directional visual sensors can provide coverage only in a fixed direction at a time.

1.1. Deployment and application of visual sensor networks

A visual sensor network can be deployed in two ways:–(i) deterministic placement, and (ii) random scattering. In deterministic placement, the visual sensors can be suitably positioned to meet the coverage requirements. However, this is only possible in a small or medium-scale network where only a specified set of sensor locations is available and/or the topography is completely known. But in reality, deployment could be in large-scale containing thousands of sensors possibly in an inaccessible terrain (such as in battlefield) where random scattering is the most convenient and (perhaps) the only option.

The real world scenarios of the large-scale randomly deployed VSNs include surveillance system, target tracking, environment monitoring, traffic controlling, and battlefield monitoring, to name a few.

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1.2. Necessity of fault tolerance in visual sensor network

The basic form of Maximum Coverage with Minimum Sensor (MCMS) problem in a VSN deals with covering maximum targets using minimum sensors. Activating minimum possible sensors is necessary for building cost-effective and energy-efficient networks. However, in real environment, a target may lose its coverage due to various reasons such as power drainage of the sensors, malfunctioning sensors, sudden appearance of obstacle(s) along the covering pan of a sensor etc. So, besides coverage we also need to deliberately introduce *fault tolerance* by covering each target with more than one sensor.

1.3. Practicality of heterogeneous coverage in visual sensor network

While providing fault tolerance one might envision a homogeneous system where every target is covered equally. However, in reality we may not need the same degree of fault tolerance for all of the targets because all of them might not be of equal importance. For example, in an educational institution, there are various places such as classrooms, common rooms, laboratory rooms, office rooms, teachers' rooms, corridors etc. All places are not of equal importance. Therefore, while building a surveillance system for such an educational institution we may need different degree of coverage for different places. Perhaps one need to be more cautious with monitoring a laboratory room (which is mainly a private space installed with costly scientific equipments) than monitoring a corridor (which is more like a public place). So, we may want to assign more sensors for covering the laboratory room than for covering the corridor. Another important motivating scenario is deployment of visual sensors in battlefield monitoring. In a battlefield, critical targets like bastions or headquarters require greater number of visual sensors than comparatively less important targets like small barracks. On the contrary, assigning the same number of additional sensors for all the targets in such scenarios may introduce too many redundant sensors substantially increasing the network installation and maintenance cost. Thus, we end up with having heterogeneous coverage requirement problem of targets in such kind of scenarios.

1.4. Types of visual sensor networks

We are concerned about two kinds of visual sensor networks:–(i) Over-provisioned, and (ii) Under-provisioned. We call a system over-provisioned if we have enough sensors to fulfill the coverage requirements of the targets, whereas, a system is under-provisioned otherwise.

1.5. Practicality of under-provisioned network

We face the problem of scarcity of sensors in real environment. We need to focus on under-provisioned networks where there are insufficient number of sensors to ensure the heterogeneous coverage requirements or fault tolerance. Even a previously over-provisioned network may become under-provisioned in course of time due to discovery of some additional new targets but the number of sensors may remain the same. Moreover sensors are costly. Thus under-provisioned networks exist in real life. In that case we may assign coverage priorities; targets with higher coverage requirement should get higher coverage. Or we may maintain a balanced coverage; targets with the same coverage requirements would get more or less similar coverage.

All of these scenarios motivate us to investigate the heterogeneous coverage problem focusing on both over-provisioned and under-provisioned networks.

1.6. Previous works and our contributions

In this section, we present the related works that are aligned with our research. Also we point out the contributions of the paper that are novel with respect to the existing works.

1.6.1. Previous works

There are two main categories of research for single coverage problem (i.e., each target requires only one sensor to get covered) in *omni-directional* sensor setting. One thread of works deals with designing online algorithm according to some off-duty eligibility rule and other thread of works deals with designing offline algorithm. Under the first thread of work (designing online algorithm), Tian and Nicolas (Tian and Georganas, 2002) introduce the idea of "sponsored area" in designing an off-duty eligibility rule to ensure complete coverage. Analysing intersection points by sensors, Wang et al. (2003) design an off-duty eligibility rule. Zhang and Hou (2005) developed Optimal Geographical Density Control (OGDC) algorithm for minimizing sensing-overlap. Under the second thread of work, researchers design (offline) algorithms for organizing sensor nodes in power-aware fashion. Megrian and Potkonjak (Meguerdichian and Potkonjak, 2003) present ILP formulations and approaches to reduce energy consumption by sensor nodes while guaranteeing single coverage of all targets. Slijepcevic and Potkonjak (2001) propose set k-cover problem where they maximize k which is the number of disjoint set covers; here a set cover refers to a set of sensor nodes which can completely cover required area. The chosen sets will be active successively along time. Adding bandwidth constraint with disjoint set cover, Cheng et al. (2005) formulate minimum breach problem where sizes of set covers are bounded; they show that network lifetime can be extended by additional bandwidth constraint at the cost of coverage breach. Following disjoint set cover approach, Cardei et al. (2005) improved network lifetime by using the same node in multiple set covers. Zhao and Gurusamy (2008) consider the Connected Target Coverage (CTC) problem with the goal of maximizing network lifetime. The objective of their work is: scheduling the sensors in multiple sets each of which can both maintain the connectivity among the sensors and target coverage. Lu et al. (2015) study the Maximum Lifetime Coverage Scheduling (MLCS) problem for WSNs, considering both data collection and target coverage. In a survey Yetgin et al. (2017) present a comprehensive discussion on network lifetime optimization in WSN.

There exists a good number of research works on k-coverage (i.e., each target needs to be covered by at least k sensors) (Yen et al.; Ammari and Das, 2010; Hefeeda and Bagheri, 2007; Bejerano, 2008) using *omni-directional* sensors. Yen et al. divide the deployment area into circular sensing regions of fixed radius centered at each available sensors and perform k-coverage of those circular regions. Ammari and Das (2010) address the k-coverage problem of wireless sensor networks in three dimensional space. Hefeeda and Bagheri (2007) solve the k-coverage problem on dense networks. Bejerano (2008) works on k-coverage problem in situation where the location of targets and sensors is not known before. Notably, none of these works are directly applicable for directional visual sensors.

Existing works in *directional* sensor networks, can be broadly classified into several categories. In one category, the coverage requirement is homogeneous; each target requires to be covered by the same number of sensors. Under this category, Ai and Abouzeid (2006) formulate the single coverage requirement (i.e., every target needs to be covered by at least one sensor) as Maximum Coverage with Minimum Sensors (MCMS) problem and devise the exact integer linear programming (ILP) solution. They also provide greedy heuristics to approximate the optimal formulation. Lu et al. (2014) study Maximum Directional Target Coverage Problem (MDTCP). They mathematically formulate the problem as a Mixed Integer Linear Programming (MILP) and propose an approximation algorithm. Cai et al. (2009) approach single coverage problem in target-oriented way. They organize sensors in cover sets and activate only one cover set at a time to increase network lifetime. Zannat et al. (Zannat et al., 2016) study the single coverage problem from target oriented approach. They provide greedy algorithm that prioritize the targets that are less coverable. They also provide approximation bounds on existing and proposed heuristics. Our work differs from Zannat et al. (2016) in many aspects: they are concerned with single coverage whereas we deal with heterogeneous coverage, i.e., coverage