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Optimal drone placement and cost-efficient target coverage

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ABSTRACT

Observing mobile or static targets in the ground using flying drones is a common task for civilian and military applications. We introduce the minimum cost drone location problem and its solutions for this task in a two-dimensional terrain. The number of drones and the total energy consumption are the two cost metrics considered. We assume that each drone has a minimum and a maximum observation altitude. Moreover, the drone's energy consumption is related to this altitude. Indeed, the higher the altitude, the larger the observed area but the higher the energy consumption. The aim is to find drone locations that minimize the cost while ensuring the surveillance of all the targets. The problem is mathematically solved by defining an integer linear and a mixed integer non-linear optimization models. We also provide some centralized and localized heuristics to approximate the solution for static and mobile targets. A computational study and extensive simulations are carried out to assess the behavior of the proposed solutions.

1. Introduction

During the recent years, we have witnessed an increased interest in using flying devices for monitoring applications. Emerging pervasive application systems, such as observation and tracking of unknown moving or static objects, will face a number of challenges, including the need to operate in extreme and unknown environments. It is important to develop reliable systems by providing the most appropriate and up to date information, at the lowest cost. The technology to observe this kind of systems, such as drones, has become increasingly prevalent and has many practical applications, including emergency or rescue operations, military operations, and environmental monitoring.

We assume drones equipped with one or more electrical motors (quadcopters) and a fixed-angle camera targeting on the ground. The drones are able to identify static or mobile ground targets, which are considered as points that have to be monitored, such as machines, animals, humans etc. We assume a binary sensing model, with isotropic sensing, and that the targets are moving on a flat and smooth area of interest. In case of mobile targets, no a priori information about their mobility is known, except their maximum speed. Our objective is the *optimal* deployment of drones ensuring, at the same time, that each target is covered by at least one drone. Another dimension in our problem is that each drone can change its coverage radius, depending on its altitude that allows it to cover more or less targets. It is assumed that the energy consumed by each drone is related to its altitude. We take into consideration an empirical energy consumption model based on our own measurements with electrical motors and drone manufacturers data. The focus of this work is the minimization of the cost, that is the number of drones or the total energy consumption. The number of drones depends on the number of targets, their dispersion, and their movement. In this paper, we minimize the total cost only in order to simplify the computational model. However, a split rule can be easily added in heuristics to decrease altitudes – and thus the energy consumption – when there is such a need. Moreover, in our localized solution, drones are always keen to retain low altitudes even if the objective is the minimization of the number of nodes.

The optimal placement of a set of monitoring devices is a very challenging problem, which, in most of the cases, has been proven to be NP-Hard (Younis and Akkaya, 2008). It is then critical to design fast, efficient and autonomous algorithms to support pervasive, "any time, any place" services in these highly mobile environments, prone to time and space evolution. Furthermore, since the system is autonomous, energy becomes a major concern.

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Hence, the energy reservation represents a fairly complex point of interest in coverage problems and constitutes a main contribution of this paper. To the best of our knowledge, this is one of the first papers that specifically deals with the cost minimization of static or mobile target tracking in the context of drones.

A simplified version of the considered problem has been addressed by the same authors in Zorbas et al. (2013), where it is assumed that an infinite number of drones is available to cover a set of mobile ground targets. In Zorbas et al. (2013), the objective is to minimize the total energy consumption. In the current paper, we handle a more general aspect of the problem under consideration by minimizing both the number of drones and the energy consumption assuming, at the same time, static or mobile targets. The introduction of non-linear restrictions as well as of a new more realistic energy consumption model makes the resulting optimization models (mixed integer non-linear programs) more complex than the ones presented in Zorbas et al. (2013). A similar problem is presented in Di Puglia Pugliese et al. (2015), where mobile targets are covered by a set of drones with limited energy resources. Each drone can be replaced by another drone if its energy has been depleted. The paper results show that solving to optimality the previous problem is a hard task even for small instances. The authors resort to heuristics based on the resolution of restricted mixed integer programs. The heuristics show very promising performance exhibiting a reasonable trade-off between quality of the solution and computational effort. The contributions and originality of this paper are:

- We mathematically formulate the optimal drone location problem. We provide a mathematical model to compute the optimal solution of the target coverage including 3-dimensional placement of the drones to cover all the targets.
- We provide an enhanced model that takes into account the energy of each drone.
- Based on the mathematical model, we design an optimal centralized solution to solve the static or mobile drone location problem.
- We propose two low-complexity centralized algorithms which provide scalable and efficient solutions to the drone location problem. The algorithms can solve instances of the considered problem with more than 50 targets and infinite possible positions for the drones. On the other hand, the optimal centralized algorithm can only provide solutions for up to 10 targets and 7803 possible positions for the drones.
- We propose a localized algorithm for the mobile drone location problem, where each drone autonomously cooperates with neighboring drones in order to minimize the cost. Some interesting split and merge mechanisms are incorporated in the localized algorithm whereas its performance is not far from the centralized algorithm.

The remainder of the paper is organized as follows. In Section 2, we discuss the "State of the art" related to the optimal placement and drone coordination problems. Section 3 introduces the optimization models, whereas Sections 4 and 5 describe the heuristic solutions. Section 6 is devoted to the presentation of the computational and simulation results collected to assess the behavior of the proposed models in terms of correctness and efficiency. The paper ends with some conclusions given in Section 7.

2. State of the art

2.1. Optimal placement

The optimal placement of static or mobile devices, for monitoring a set of targets, has already been studied in the literature from different aspects. The works closest to ours deal with the design of optimization strategies that deterministically place nodes in order to meet specific goals such as coverage and network longevity (Kar and Banerjee, 2003; Navarro-Serment et al., 2004; MartíNez and Bullo, 2006; Dasgupta et al., 2003; Wang et al., 2006). In contrast to the drone location problem, where the machines can change their altitude and, thus, reduce or increase the coverage area, the targets are monitored by wireless sensor nodes with fixed monitoring range. However, the optimal node placement problem can be transformed to an optimal drone location problem, considering that the nodes can adjust their monitoring range to cover more or less targets. Other similar node placement problems are the relay node placement and placement of data collectors. A thorough review of these works is done in Younis and Akkaya (2008).

Other optimization problems deal with the positioning of cameras for surveillance systems (González-Banos, 2001; Bodor et al., 2007; Ercan et al., 2006). The purpose of the placement is to provide full coverage of a whole area as well as the highest resolution images of objects and motions in the scene that are critical for the performance of some specific task. This kind of problems differs to the drone location problem since the position of the camera is horizontal.

2.2. Similarities with sensor networks

The drone location problem with adjustable heights is similar to the node deployment problem of wireless sensor networks with adjustable sensing ranges. In this kind of networks a number of nodes are deployed to cover some targets or area while the nodes can adjust their sensing radii to conserve energy. Important information about this similar problem can be found in Bartolini et al. (2012), Cardei et al. (2005b), Dhawan et al. (2006), and Zhou et al. (2009). Most of these works deal with the problem of computing the maximum number of cover sets such that only one set is active at any time and each set covers all the targets. Adjustment of radii is used as an option of reducing the energy cost and, thus, increasing the number of sets. This type of scheduling problems are proven to be NP-Complete (Cardei et al., 2005a).

2.3. Vehicle coordination and coverage

The use of flying machines for monitoring purposes is an important task which has attracted a lot of research effort, in the recent years. We use the term "coverage" to refer to a wide range of problems related to target tracking, area discovery, area patrol, quality of detection, and navigation. On the other hand, drone coordination is usually limited to (a) how a fleet of machines can cooperatively monitor a number of ground targets as well as to (b) static or dynamic machine routing problems, related to the computation of an optimal trajectory.

A relevant big part of the literature is dedicated to coverage requirements and mainly to how well objects are tracked by sensors (e.g. cameras) attached to the drones. In Sinha et al. (2004) and Gu et al. (2006) a target detection problem is considered where a group of drones detects the position of targets using sensors located on the machines. Real vision-based drone navigation and guidance systems are presented in Watanabe et al. (2010) and Brown et al. (2006). This kind of systems is capable of localizing targets and estimates their position. In Zhu et al. (2013), an approach that guarantees the global convergence of a single drone to a desired orbit around a target is proposed. Constant background wind and target motion are, also, taken into account. In Kim and Kim (2008) and Wang et al. (2010) algorithms to cooperatively track a moving target by several drones are proposed.