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Optimizing watchtower locations for forest fire monitoring using location models

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ABSTRACT

Automated forest fire monitoring systems can be constructed using forest fire watchtowers equipped with laser night vision cameras or high-definition video cameras. In order to minimize the construction cost and to maximize the monitoring coverage of forest fires, efficiently placing the watchtowers is critical. This paper examines efficient watchtower locations by integrating visibility analysis and location-allocation models. Specifically, based on the classical location set covering problem and maximum covering location problem, three optimization models are developed to satisfy three kinds of requirements of forest fire monitoring in practice: minimizing cost with full coverage, maximizing coverage with a fixed budget, and maximizing coverage while minimizing the cost. The models are tested using integer programming and a multi-objective genetic algorithm, with an application in a forest park in Guangzhou, China. The results suggest that this model-based optimization approach to watchtower location can be used to improve the efficiency of forest fire alarm systems.

1. Introduction

Forest fire is a severe natural disaster and public emergency of the world. Fire incidents are often abrupt, spread rapidly, difficult to control, and highly disastrous, and have become a serious threat to forest resources globally as they affect forest ecosystem succession and global climate change. According to a report of Greenpeace Research Laboratories and climate change research of United States Environmental Protection Agency, there has been an increase in the number of forest fires because of global warming and intense human activities [1,2]. In recent years, forest fires, known as wildfires, consumed more than 6.25 million acres of forest in Alaska (roughly equal to the area of Massachusetts) [2]. Climate change is projected to increase the extent, intensity, and frequency of wildfires in certain areas of our earth. Forest fires have also become a major concern in China in recent decades because of the increasingly serious damage they have done to the environment and the loss of societal wealth incurred. According to a report on Chinese forestry development, a total of 3966 forest fire incidences were identified in 2012, and China spent ¥342,000,000 fighting forest fire, and the government invested more than 2 billion Yuan on 190 construction projects to prevent forest fire [3].

Among many preventive measures, early detection and suppression of forest fires are the main ways to minimizing damage. The critical issue in forest fire monitoring systems is the immediate response in order to minimize the scale of destructions. Many countries that have recognized the significant importance of forest fire monitoring have developed effective technologies, including monitoring via observation towers, cruising aircrafts, remote sensing using meteorological satellites, and sensor networks, to improve their response ability [4–8]. Forest fire monitoring technology was implemented belatedly in China but has experienced a rapid growth, with watchtowers being the first selection for forest fire monitoring in the country. In the light of the 2013 report of Chinese forestry development, for example, various preventive and monitoring measures have been implemented, and the coverage rate of forest fire monitoring has increased from 45.3 to 63.1 percent in China [3]. Since December 2013, the Administration of Forestry and Gardening of Guangzhou Municipality launched a project of 74 million Yuan to monitor fire of key forest zones and green parks by video cameras, which will equip 941 cameras to cover 8 parks, 3 forest farms, and 2 forest and wild animal protection areas [9].

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Protecting wild animals, forests, and the environment from forest fires has long been a major concern in environment and natural resources management [10]. In the past, forest personnel monitored fires from watchtowers that were located on hilltops in forests so that forest fires could be discovered and alarmed as soon as possible [6,7]. However, living conditions are often difficult at lookout towers for human observations who may also lack the consistency and reliability required for constant monitoring. As a result, vision techniques such as automatic video surveillance systems (AVSS) were proposed to monitor small forests [8]. Many medium and large-scale fire surveillance systems currently do not accomplish timely detection because of low resolution or long periods between scans [6,7]. With developments in technology, high definition video cameras and sensor networks are now being used to equip watchtowers and automate forest fire monitoring. Further, watchtowers can be equipped with solar panels that supply power to support the compression of images and real-time transmissions to command centers via wireless networks. Forest fire watchtowers equipped with laser night vision cameras or high-definition video cameras can constitute an automated forest fire monitoring system that has a wide coverage of monitoring viewsheds and can quickly respond to forest fire alarms (Fig. 1).

Determination of the optimum location of permanent fire watchtowers in a given forest area has been, and continues to be, of significant interest to both the practitioners and research communities [11,12]. The efficient location of watchtowers equipped with cameras has become increasingly important as it can directly influence the construction cost of watchtowers and the monitoring coverage of forest fires [13]. It is a combinatorial optimization problem and, consequently, is difficult to obtain optimal location solutions using simple enumeration and search methods or viewshed analysis based on geographic information systems (GIS). Further, watchtowers need to be sited optimally to meet forest fire monitoring requirements such as full coverage, maximal coverage, minimal cost, and/or minimum overlap for forest fire monitoring. There are also specific constraints such as terrain limitations and the effective detection range of cameras installed on watchtowers of various heights.

This paper proposes a modeling approach to optimizing the spatial coverage of watchtowers equipped with cameras in forest zones. This approach integrates coverage models and visibility analysis into a spatial optimization framework and applies the result to forest fire monitoring. The aim of the approach is to develop a procedure for finding optimal solutions of locating watchtower that satisfy a set of objectives and specific constraints of forest fire monitoring in practice. In the remainder of this paper, Section 2 analyzes technical problems associated with forest fire electronic monitoring, Section 3 presents the three proposed optimization models, Section 4 outlines the implementation procedure for the three models and discusses the application results obtained, and Section 5 summarizes and concludes this paper.

2. Problem analysis

When a watchtower is planned for construction on an undulating terrain, a major concern is the tower's viewshed, meaning a set of locations on the terrain that are visible from the watchtower extending out to the maximum visibility distance of the camera. Viewshed analysis is an important function of GIS as a method of visibility analysis based on the terrain and has been successfully applied in many applications [14–17]. The viewshed of a watchtower is computed and analyzed at each candidate location based on a digital elevation model (DEM) from which the elevation of each cell is used to determine the visibility to or from a candidate position when applied to forest fire monitoring [17]. Usually the candidate positions for building watchtowers are the many hilltops in the forest, as illustrated in Fig. 2. The viewshed of a watchtower is subject to the height and position of the hilltop and tower, the maximum visibility distance of the camera, and the undulating terrain in a given forest area. A location or a cell in the DEM is considered to be covered if it is within the viewshed of a watchtower, in which a cell value of one signifies the primary coverage meaning the cell is covered by only one tower. Cells with a value of zero are gaps between viewsheds, and fire monitoring blind zones that are at risk of forest fire disaster.

Watchtowers need to be sited optimally to obtain maximal coverage or minimal cost for forest fire monitoring, taking into account terrain conditions and the effective detection range of the cameras mounted on watchtowers at various heights. While viewshed analysis can be used to provide useful information for siting watchtowers, the method alone cannot generate optimal watchtower locations. Instead, optimization models must be used to help search for watchtower locations in order to satisfy a set of requirements of watchtower regarding monitoring coverage and construction costs. Two optimization models are of particular importance in this research. When watchtowers must monitor the entire forest area, the location set covering problem or LSCP [18] can be used to minimize the total construction cost while guaranteeing that each cell is covered at least once. ReVelle [18] also studied the use of multiple types of facility to fully cover the demands with an objective to minimize the number of facilities in the LSCP as a way of minimizing the cost. While complete coverage of watchtowers to cover all demands is ideal, it is sometimes economically infeasible due to budget constraints. In this case, the maximal covering location problem, or MCLP, is used so that the

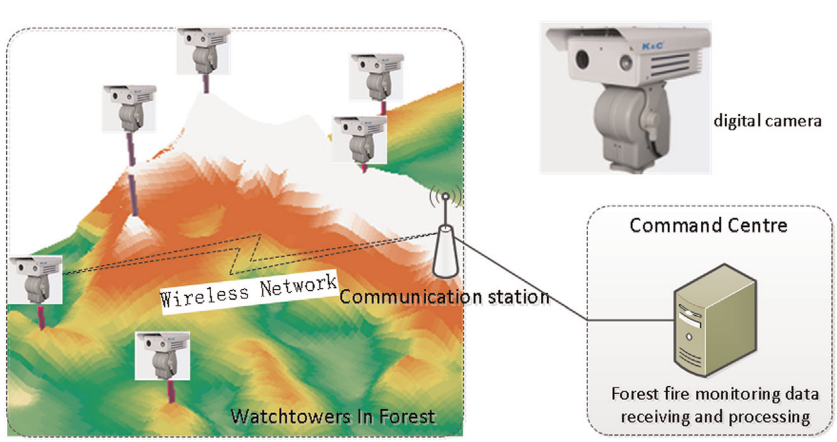

Fig. 1. Automated forest fire monitoring system.