European Journal of Operational Research 000 (2018) 1–16

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Discrete Optimization

Optimizing source and receiver placement in multistatic sonar networks to monitor fixed targets

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ARTICLE INFO

Article history:
Received 21 December 2015
Accepted 1 February 2018
Available online xxx

Keywords:
OR in defense
Sensor placement
Optimization
Multistatic sonar

ABSTRACT

Multistatic sonar networks consisting of non-collocated sources and receivers are a promising development in sonar systems, but they present distinct mathematical challenges compared to the monostatic case in which each source is collocated with a receiver. This paper is the first to consider the optimal placement of both sources and receivers to monitor a given set of target locations. Prior publications have only considered optimal placement of one type of sensor, given a fixed placement of the other type. We first develop two integer linear programs capable of optimally placing both sources and receivers within a discrete set of locations. Although these models are capable of placing both sources and receivers to any degree of optimality desired by the user, their computation times may be unacceptably long for some applications. To address this issue, we then develop a two-step heuristic process, Adapt-LOC, that quickly selects positions for both sources and receivers, but with no guarantee of optimality. Based on this, we also create an iterative approach, Iter-LOC, which leads to a locally optimal placement of both sources and receivers, at the cost of larger computation times relative to Adapt-LOC. Finally, we perform computational experiments demonstrating that the newly developed algorithms constitute a powerful portfolio of tools, enabling the user to slect an appropriate level of solution quality, given the available time to perform computations. Our experiments include three real-world case studies.

1. Introduction

Sonar systems have been in use in undersea and antisubmarine warfare for decades. During this time, they have evolved and found application in non-military fields, such as depth-finding, position marking, communication and telemetry, and aiding fishermen, divers, and conservationists (Urick, 1983). Researchers and practitioners distinguish between active and passive sonar systems as well as between monostatic and multistatic systems. A passive sonar system consists solely of receivers that “listen” for objects in the environment. An active sonar system contains at least one source and receiver. The source sends out a pulse of underwater sound, called a ping, which is reflected by objects in the underwater environment. The reflected signal is detected by a receiver, and using this signal it is possible to determine information about the objects in the vicinity, including their locations. A monostatic sonar system consists of sensors called posts; each post contains both a source and receiver (Ozols & Fewell, 2011). This principle is illustrated in Fig. 1 (left). In a multistatic sonar network (MSN),[3] sources and receivers are not necessarily collocated; see Fig. 1 (right). In the multistatic case, sources and receivers can consist of free-floating sonobuoys, or they can be mounted on ships or dipped by helicopters. A MSN has numerous advantages compared to a monostatic system. These advantages include reduced cost, more complicated countermeasures, increased flexibility, and higher precision with fewer pings. However, these advantages come at the cost of increased mathematical complexity in evaluating MSN system performance. The complications with MSNs arise due to the different geometry in comparison to the monostatic case. In the monostatic case the detection probability depends largely on the distance between post and target. In case of a multistatic constellation, the distances between target and source as well as target and receiver are relevant (Fewell & Ozols, 2011). As

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[3] All acronyms used in this paper appear in Table 4 in the appendix.

https://doi.org/10.1016/j.ejor.2018.02.006
0377-2217/© 2018 Published by Elsevier B.V.

Please cite this article as: E.M. Craparo et al., Optimizing source and receiver placement in multistatic sonar networks to monitor fixed targets, European Journal of Operational Research (2018), https://doi.org/10.1016/j.ejor.2018.02.006

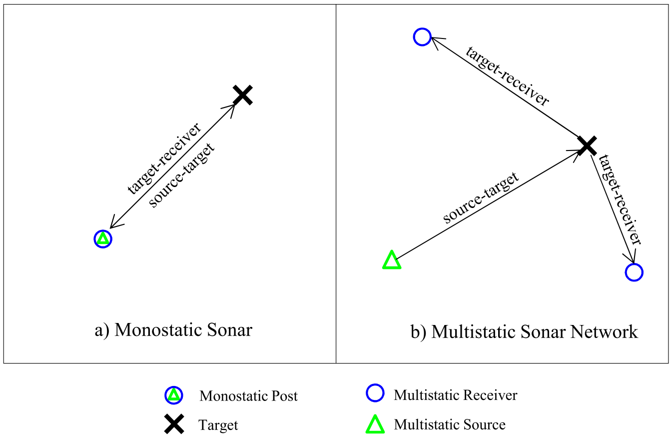

Fig. 1. Geometry of sonar detection for the monostatic case (left) and multistatic case (right).

a result, it is considerably more difficult to determine optimal positions for sources and receivers than for monostatic posts.

The problem of determining optimal positions for sensors in a MSN is also closely connected with facility location problems (FLPs), in particular with planar location or continuous facility location problems (CFLPs). In a CFLP, facilities are allowed to be located anywhere in an area of interest, as opposed to being restricted to a finite set of pre-identified locations (Arabani & Farahani, 2012; Carlo, Aldarondo, Saavedra, & Torres, 2012). Some problems that have been modeled as CFLPs include determining locations for Wi-Fi access points at airports, recreational areas, pollution sensors for environmental monitoring, and military surveillance devices (Revelle, Eiselt, & Daskin, 2008).

The literature on CFLPs is abundant and several models and solution techniques have been developed to address particular variants of the CFLP. For example, Redondo, Fernández, García, and Ortigosa (2009) study the CFLP problem in a competitive setting, where other facilities offering the same product or service already exist in the area. The authors solve the problem with three different heuristics approaches: a simulated annealing algorithm and two variants of evolutionary algorithms. Wong and Sun (2001) consider a heterogeneous continuous space with a set of competitive facilities and incorporate congested transportation costs between demand and facility nodes. They formulate the model as a combined distribution and assignment model and solve it with an iterative algorithm. On the other hand, Matisziw and Murray (2009) consider the problem of siting a facility in continuous non-convex space to maximize coverage. In contrast, Carlo et al. (2012) consider determining both the number and location of new facilities simultaneously with the objective of minimizing the total cost of interacting with a set of existing facilities. The researchers develop a nonlinear mixed integer mathematical model, a brute-force algorithm, and four heuristics, and they show that a greedy search heuristic outperforms all other heuristics considered. In a more recent study, Brimberg, Juel, Körner, and Schöbel (2015) study the CFLP under the assumption that a facility is allowed to cover a demand point partially. Although our problem can be considered to be a CFLP, it is clearly different from the other CFLP variants previously studied due to the presence of two types of “facilities” and the particular way these facilities interact in determining the objective value.

Despite the widespread use of multistatic sonar systems in practice, the literature contains relatively few analytical results to guide practitioners. Most of the existing studies present heuristic approaches or seek to evaluate a rule-of-thumb approach. For example, George and DelBalzo (2007) and Tharmarasa, Kirubarajan, and Lang (2009) use genetic algorithms to select locations for multistatic sensors for area coverage and tracking purposes. Ngatchou, Fox, El-Sharkawi et al. (2006) develop a particle swarm method to determine the number and placement of multistatic sensors to maximize area coverage. Similarly, Ozols and Fewell (2011) study the area coverage problem and analyze the coverage performance of 27 MSN layouts to determine the most cost effective pattern. Strode (2011) uses game theory to select multistatic sensor positions in order to detect a transiting intelligent underwater target; he then integrates this approach into the Multistatic Tactical Planning Aid (MSTPA), a decision support tool developed at the Centre for Maritime Research and Experimentation (CMRE). Kalkuhl, Wiechert, Nies, and Loffeld (2008) develop a simulation-based methodology for planning multistatic search and rescue missions. Casbeer, Swindlehurst, and Beard (2006) study the problem of connectivity in a mobile multistatic radar network containing unmanned air vehicles (UAVs). They develop a metric that provides for a balance between the performance and connectivity of the network. Gong, Zhang, Cochran, and Xing (2013) study another type of coverage problem: the barrier coverage problem, in which sensors are deployed on a line segment. They determine a placement order and spacing of sensors which minimizes the vulnerability of the network to intruders. Incze and Dasinger (2006) analyze the performance of a MSN by using a combined Monte Carlo simulation and Bayesian integration technique. They use this methodology to account for uncertainties such as target behavior and target probability distribution. In another study, Bowen and Mitnick (1999) develop a multistatic performance prediction methodology which can be used to assess the detection performance of a MSN as a function of source and receiver densities. Walsh, Wettergren et al. (2008) compute the expected detection probability of a given target track in a MSN field where all sources and receivers are distributed uniformly at random. Similarly, Washburn and Karatas (2015) consider a randomly deployed MSN and develop an analytic theory that measures the coverage of the network as a function of source and receiver densities. Karatas, Gunal, and Craparo (2016) use simulation to investigate the coverage performance of a mobile source performing parallel sweeps in a field of stationary receivers, and they compare their results by those of the analytic formulae developed by Washburn and Karatas (2015).

The aforementioned studies only consider the area coverage, barrier coverage, and tracking performance of a MSN. In contrast, Craparo and Karatas (2018) study the point coverage problem, in which the goal is to position sources in such a way as to cover as many of a finite number of target locations as possible, given fixed receiver locations. Their approach begins with a preprocessing algorithm that determines a polynomially-sized set of possible source locations guaranteed to contain the optimal source locations. Once this preprocessing is finished, source locations must be selected from among the set of candidate locations. Craparo and Karatas (2018) formulate an integer linear program that optimally selects source locations, and they also describe an efficient approximation algorithm for selecting source locations. In another study considering the point coverage problem, Craparo, Karatas, and Kuhn (2017) derive various results useful for excluding some suboptimal sensor locations, and they describe the Divide Best Sector (DiBS) algorithm for optimally placing a single source in a field of fixed receivers under a diffuse sensor model. In our computational experiments, we compare our algorithms' performance to that of Craparo and Karatas (2018), since their assumptions and overall problem setup most closely match our own.

Currently, no algorithm exists for selecting optimal sensor locations for both types of sensors (sources and receivers) for the point coverage problem. This capability is clearly desirable for practical multistatic operations, as in the case of a maritime patrol

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