Expert Systems with Applications 40 (2013) 3886–3899

Contents lists available at SciVerse ScienceDirect

Expert Systems with Applications

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

A decision support system for optimal deployment of sonobuoy networks based on sea current forecasts and multi-objective evolutionary optimization

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ARTICLE INFO

Keywords:
Dynamic sensor networks
Optimal deployment
Multi-objective evolutionary optimization
Decision support systems
Ensemble forecasts
Surveillance

ABSTRACT

A decision support system for the optimal deployment of drifting acoustic sensor networks for cooperative track detection in underwater surveillance applications is proposed and tested on a simulated scenario. The system integrates sea water current forecasts, sensor range models and simple drifting buoy kinematic models to predict sensor positions and temporal network performance. A multi-objective genetic optimization algorithm is used for searching a set of Pareto optimal deployment solutions (i.e. the initial position of drifting sonobuoys of the network) by simultaneously optimizing two quality of service metrics: the temporal mean of the network area coverage and the tracking coverage. The solutions found after optimization, which represent different efficient tradeoffs between the two metrics, can be conveniently evaluated by the mission planner in order to choose the solution with the desired compromise between the two conflicting objectives. Sensitivity analysis through the Unscented Transform is also performed in order to test the robustness of the solutions with respect to network parameters and environmental uncertainty. Results on a simulated scenario making use of real probabilistic sea water current forecasts are provided showing the effectiveness of the proposed approach. Future work is envisioned to make the tool fully operational and ready to use in real scenarios.

1. Introduction

Decision making and operation planning in the maritime environment is a difficult task, since it is strongly affected by meteorological and oceanographic (METOC) conditions. In the last years, several maritime decision support systems have been proposed in literature (Grasso et al., 2010a, Grasso, Cococcioni, Trees, Rixen, & Baldacci, 2010b, 2011, 2012), to support the decision maker in operations at sea, such as naval refueling, amphibious landing and diver operations, by assessing the impact of the environment on operation effectiveness and defining an optimal course of action by optimizing risk metrics, mission costs and sensor performance. In this paper, the problem of deploying a network of sonar buoys (a particular type of wireless sensor network) for cooperative track detection is considered (Baumgartner, Ferrari, & Wettergen, 2009; Le Cadre & Souris, 2000). The goal is to assist the operation planner on where to deploy each sensor, in order to maximize multiple performance measures during the whole mission, by taking into account the fact that the sensors will drift because of the sea currents (Baumgartner et al., 2009).

Sonobuoys (short for sonar buoys) are expendable sonar systems which can be deployed from airplanes and/or ships and are able to detect and possibly identify objects moving in the water, threatening a particular area of interest. They find application in security and defense applications, like border and harbour protection and maritime surveillance. Sonobuoys can be passive or active, directional or non-directional. A passive sonobuoy is equipped with an acoustic receiver (hydrophone) which detects acoustic energy emitted by remote sources. An active sonobuoy, in addition, mounts a transducer to radiate a sonar pulse that is reflected back from targets. In a non-directional sonobuoy, the hydrophone receives energy from all directions, while in a directional sonobuoy the receiver detects energy from a limited angular field of view. Similarly, the transducer, in an active configuration, can emit energy omni-directionally or in a smaller angular beam. In this paper, non-directional passive sonobuoys are considered. They are composed of a surface float equipped with a radio transmitter able to communicate with a base station (sometimes on board an airplane), a hydrophone attached to the buoy with a cable that keeps the sensor at a defined depth, a drogue and a stabilization mass at the end of the cable. Target localization is achieved by triangulation.

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http://dx.doi.org/10.1016/j.eswa.2012.12.080

A number of sonobuoys can be deployed in the area of interest to form a wireless sensor network having an architecture that is usually centralized with a base station serving as a central data fusion node. The performance of sonobuoy networks typically degrades with time due to sensor drift and acoustic variability in the surveillance area (Baumgartner et al., 2009). Due to the uncontrollable drifting movement of sensors, the detection area covered by the network and the number of sensors able to detect a target entering the area of interest from a particular direction can significantly change over time (Baumgartner et al., 2009). The spatial and temporal acoustic variability of the area of interest further affects the network performance due to variations of the effective detection range of sensors (Baumgartner et al., 2009).

In order to achieve an almost constant level of network quality of service in a specified temporal window, the initial position of each sonobuoy can be chosen by optimizing a set of objectives, with the dynamic of the network and the sensor characteristics as constraints. This technique is referred to as dynamic sensor network optimal deployment (OD) and is alternative to other common methods like the random and the grid deployment ones (Baumgartner et al., 2009). OD requires integrating sea water current forecasts, acoustic propagation models and sonobuoy drifting models, a process that could not be afforded by the operation planner without an integrated decision support system (DSS) environment that acquires data over the area of interest in a predefined time window, integrates data and mission parameters in an optimization scheme, provides and ranks solution hypothesis, and tests solution robustness against environmental and non-environmental uncertainty.

In this paper, a DSS for OD of dynamic sensor networks is proposed and tested on a synthetic scenario. The main modules of the system are (i) a network simulator to predict sensor trajectories given a 4D forecast of the current field, (ii) a network performance calculator given sensor trajectories and sensor effective detection range predictions, (iii) an optimizer to provide OD solutions (i.e. initial sensor positions) and (iv) a sensitivity analysis module to test the robustness of the solution against the uncertainty of the environment and network parameters. The proposed framework follows the seminal paper on OD for cooperative track detection by Baumgartner et al. (2009), who first developed the technique by optimizing the weighted sum of the mean network area coverage (AC) and the mean $k-N$ track coverage ($k-N$ TC) quality of service indexes (both defined in next section). This work tries to overcome some limitations of the optimization scheme proposed in Baumgartner et al. (2009) by using an evolutionary multi-objective optimization algorithm to give to the user the flexibility of evaluating a full set of Pareto efficient solutions (Coello Coello, Lamont, & Van Veldhuizen, 2007; Deb, 2001) representing tradeoffs between conflicting performance metrics.

1.1. Related works

The problem of cooperative track detection was introduced for the first time in Le Cadre and Souris (2000). In Ferrari (2006) and Baumgartner and Ferrari (2008) a geometric transversal approach was used to provide a measure of track coverage in sensor networks. In Ferrari, Zhang, and Wettergren (2010), the geometric transversal approach was compared with the distributed-search theory (Wettergren, 2008) for deriving the probability of track detection in sensor networks and showed that the two approaches are equivalent under certain hypothesis. In Baumgartner and Ferrari (2007) and subsequently in Baumgartner et al. (2009) the OD of dynamic sensor networks by optimizing integrated AC and TC metrics, constrained by the network dynamic, was first derived and applied. A sequential quadratic programming technique with a weighted sum of objectives was used as the optimization scheme. The use of a global multi-objective optimization algorithm has not been investigated therein.

In DelBalzo, Kierstead, and Stangl (2005) a genetic algorithm has been used to optimize both the location and the ping times in active sonobuoys. In Rajagopalan, Mohan, Mehrotra, and Varshney (2008) and Sakr and Wesolkowski (2011) wireless sensor network design and management using multi-objective evolutionary optimization has been investigated with success, demonstrating the capability of the optimization scheme in providing a good choice of Pareto efficient solutions that the network designer can explore in order to match operational needs. However these works do not consider the problem of deploying the network in the dynamic and uncertain future ocean environment.

1.2. Organization of the paper

The paper is organized as follows. Section 2 is devoted to problem statement and to the description of the adopted solution, with a review of the state-of-the-art of multi-objective evolutionary algorithms. Section 3 shows the experimental results, while Section 4 discusses the implications of the present work. Finally Section 5 summarizes the work, draws conclusions, and proposes future work.

2. Problem statement and adopted approach

Given a set of N sensors, the problem consists of deciding where to deploy them over a region of interest (ROI) at sea, in order to maximize both the area coverage and the probability of detection of threats crossing the ROI along straight lines, for the whole duration of the mission. The mission endurance is bounded by the battery lifetime of sonobuoys sensors. Most sonobuoys are set to scuttle after a preset time, typically 1, 3, or 8 h. This prevents radio frequency (RF) channels from being blocked by an RF transmitter from a buoy that is no longer of interest. The problem is complicated by the fact that sea currents cause the drift of the sensors over the surface (we are assuming surface sonobuoys, i.e., buoys which float at the sea surface).

2.1. The adopted approach

The proposed solution to the OD problem is based on simulating future tracks of network sensors by using a simple kinematic model of a drifter forced by an ocean circulation forecast model. Sea water current predictions are provided by a super-ensemble forecast model which is also able to estimate prediction error statistics. These statistics are used after the optimization step in the sensitivity analysis to assess the impact of the environmental uncertainty on the set of solutions found.

Multi-objective genetic algorithms are used to optimize the deployment of the network as described in detail in the next sections. The optimization is directly performed in a multi-dimensional objective space, by exploiting the concept of Pareto dominance (Coello Coello et al., 2007; Deb, 2001), thus avoiding specifying weights among objectives (which is almost a subjective practice) as in an optimization scheme using a weighted sum of different objectives. Moreover, there is no need to know derivatives of the objectives with respect to initial positions as a genetic evolutionary technique is used. The optimizer provides a full spectrum of optimal solutions (representing different tradeoffs among objectives) close to the so called Pareto optimal front (also known as *Pareto efficient frontier*): such a set of tradeoffs can be analyzed by the mission planner for making his final decision taking into account his subjective preferences and qualitative evaluations.

The sensitivity analysis with respect to uncertainty in the environment, deployment positions and other network parameters is performed more efficiently than classical Montecarlo techniques by approximating confidence intervals of sensor track predictions