Tactical Planning with Genetic Algorithms for Multi-static Active Sonobuoy Systems

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ABSTRACT
Oceanographic and acoustic conditions in littoral environments are so complex and dynamic that spatial and temporal variability of low-frequency signal and noise fields destroys the basic homogeneous assumption associated with standard tactical search concepts. Genetic Algorithms (GAs) have been applied to this problem to produce near-optimal, non-standard search tracks for monostatic mobile sensors that maximize probability of detection in such inhomogeneous environments. The present work describes a new capability, SCOUT (Sensor Coordination for Optimal Utilization and Tactics), to optimize the locations of multistatic active sonobuoys in a complex, littoral environment. This work reviews the GA approach, discusses the chromosome structure, and introduces a new target-centric geometry. The results show that a) standard patterns are grossly ineffective in inhomogeneous environments where 20-30% improvements in detection are achieved with SCOUT, and b) small distributed sensor clusters are preferred in homogenous environments. The Naval Air Systems Command supported this work.

INTRODUCTION
Optimal monostatic sonobuoy fields were developed during the Cold War for deep, uniform undersea environments, where a simple median detection range defined a fixed spacing between sonobuoys. Oceanographic and acoustic conditions in littoral environments are so complex and dynamic that spatial and temporal variability destroys the basic homogeneous assumption associated with standard tactical search concepts. There have been several attempts to design near-optimal placements of passive and monostatic-active sonobuoys. Most of these are evaluation algorithms, as opposed to true planning algorithms.

The Genetic Range-Dependent Algorithm for Search Planning (GRASP) was developed to support ASW operations in littoral environments [1-5]. The tactical portion of GRASP is the Operational Route Planner (ORP), which uses Genetic Algorithms (GA) to create search paths in complicated environments. As originally implemented, ORP supported passive and monostatic-active sensors (e.g., traditional passive and active sonar) carried on mobile platforms (e.g., ships or aircraft). During this work, we modified ORP to include bistatic sonobuoys (sources and receivers) and bistatic receivers carried on mobile platforms. We refer to this new capability as BiORP. The new search planning system is SCOUT (Sensor Coordination for Optimal Utilization and Tactics) which uses BiORP to plan jointly optimized search paths for mobile platforms, and positions and “ping” times for bistatic sonobuoys.

Our first goal in this project was to include bistatic sonobuoy fields in the search plan while preserving all of ORP’s capabilities for planning ship search paths. For that goal it might have been sufficient to design a second algorithm for planning sonobuoy searches, and then a third for partitioning the search area between sonobuoys and ships. However, previous experience with multiple-searcher optimization [3] showed that ORP often created synergistic coordinated searches, so our second goal was more ambitious. We wanted an algorithm that would jointly optimize ship and sonobuoy plans, taking advantage of any possible synergies.
While there are many software systems that assist in search planning, the core GAs in GRASP and SCOUT are the only existing capabilities that design actual search paths (and now sonobuoy placements) from scratch, as opposed to either recommending general allocations of effort or simply evaluating standard search patterns with different parameters.

**SCOUT SYSTEM**

SCOUT is a search planning system designed for the complex acoustical environment of the littoral zone (coastal). The final goal for the project is an effective, accurate ASW search planner that can be utilized on the sea or in the air, that is, a planner that can determine a near-optimal search tactic without high performance computing or long processing time. Currently, SCOUT consists of three major components. First is ORP (Operational Route Planner), a search planning/evaluation tool that will be described in detail later. Second is a target-centric acoustical transformation, which creates a data format that reduces error and computing time. Third is EAGLE (Efficient Adaptive Gridder for Littoral Environments), a gridding system that takes advantage of variations in uncertainty to reduce inefficiencies in computing effort.

**Genetic Algorithms**

Genetic algorithms (GAs) are an attempt to find good solutions to otherwise intractable problems by mimicking evolution. A somewhat simplistic view of evolution is that it depends on five ingredients: a population of individuals, each described by a chromosome; a reproductive mechanism (either sexual or asexual); mutation; and natural selection (survival of the fittest). A chromosome is a sequence of genes, each of which describes some aspect of the individual’s structure. The chromosome as a whole completely determines the individual’s characteristics, and in particular, its fitness. Natural selection tends to eliminate the least fit individuals in favor of the most fit, leaving the most fit to pass on their genes to the next generation.

The GA mimics the process of evolution by selecting good solutions to a problem over bad ones. The chromosome identifies a single solution via a set of characteristics. Fitness is determined by an objective function (e.g. cumulative detection probability). Natural selection is mimicked by choosing solutions to reproduce with probability proportional to their fitness. Sexual reproduction is accomplished by exchanging segments of the parent solutions. Mutation is applied to the offspring by randomly perturbing some aspects (genes) of the trial solution.

**The Operational Route Planner (ORP)**

There have been many attempts to design near-optimal placements of passive and monostatic-active sonobuoys. ORP addresses the problem of designing a set of fixed-speed search paths (one for each searcher), in continuous space and time, for a fixed time period, through a connected search region, described as a polygon, with the intention of detecting a moving target, whose tactics may be modeled probabilistically. The intended application is designing anti-submarine sonar searches, where the underlying instantaneous detection functions (one for each searcher), may be specified as functions of the searcher-target geometries and locations. The details of the detection functions depend on target and searcher characteristics, including submarine target strength, and the acoustic environment. The target strength can be either omni-directional (i.e., a single value) or fully bistatic (i.e., a function of two angles and containing a large specular reflection). The evaluation metric is the Cumulative Detection Probability (CDP) at the end of a search period.

**Target-centric Geometry**

BiORP (Bistatic ORP) adapts the ORP algorithm to bistatic sensors and sonobuoy fields. As in the monostatic case, we use off-line calculations to tabulate Signal Excess (SE) at a grid of points. However, near a given acoustic grid point, monostatic SE depends only on the range and azimuth from the sensor to the target, and so can be tabulated on a polar grid of target locations with the sensor at that acoustic grid point. Bistatic SE depends on the full source-target-receiver geometry, which requires a four-dimensional table at each acoustic grid point. When SE is required, BiORP rigidly translates the entire source-target-receiver geometry so that the target is at the nearest acoustic grid point, computes the ranges and azimuths from the target to the source and receiver, and then looks up the SE in a four-dimensional table.
The structure of the SE file is an original innovation that exploits properties of ORP. We chose to structure the bistatic SE file about the target rather than the source or receiver because the primary contribution to bistatic SE is the source-to-target-to-receiver transmission path. The source-receiver geometry enters the SE calculation through direct-blast masking and reverberation. BiORP calculates direct-blast masking internally, and reverberation is much less sensitive to the precise source-receiver geometry than SE is to, say, the source-to-target range. Centering the table lookup on the target allows coarser resolution in azimuth, thus reducing the amount of SE data that must be computed and stored.

RESULTS FOR INHOMOGENEOUS ENVIRONMENT

In this example, oceanographic and acoustic conditions and sensor performance vary across the search region. In particular, we have created four 15 x 15 nmi quadrants with poor monostatic performance (2 nmi detection range) in the NE quadrant and successively better performance (4, 6, and 8 nmi detection ranges, respectively), moving in the counter-clockwise direction. Four scenarios are considered and displayed in Fig. 1. In all four, the environment is characterized by: a) 1 deg x 1 deg search region, b) 6-hr search duration, c) 8 (or 16) sonobuoys, each with a source and receiver, d) sonobuoy field laid prior to the start of search, and e) target on a random patrol at 5 kt, changing course at exponentially distributed times, with a mean time between course changes of 2 hr. Eight and 16-buoy solutions are given in the left and right columns, respectively. Solutions for bistatic and omni-directional target strength models are examined in the top and bottom rows, respectively, and correspond to bistatic and monostatic sonobuoy systems. As shown in Fig. 1, the white disks are the SCOUT solutions, while the connected gray dots represent the best possible (highest collective CDP) circular pattern, which is a common tactic.

Figure 1. SCOUT optimized patterns (white disks) and best circular patterns (connected gray dots) in inhomogeneous environments for 8 buoys (left), 16 buoys (right), bistatic target strength (upper), and omni-directional target strength (lower).

Standard search-theoretic principles for monostatic systems dictate that search effort should be applied first in the highest detection range area until the conditional target density is reduced to the point that the marginal return on effort is equal to or below that of the next-highest detection range area. Searching then moves into that area and continues until it is no longer profitable, and so on. For the monostatic buoy example of Fig. 1, buoys should be deployed in the high-detection SE quadrant until the probability of detecting targets is reduced to the point that it is more advantageous to place additional buoys in the next-highest detection range area, i.e., the SW quadrant.

Effort should only be expended in the NE quadrant (lowest detection range) if there are sufficient assets to cover all other quadrants first with a reasonably high CDP. Moreover, the marginal return on effort should decrease more quickly in the SE quadrant than in any other quadrant, as each additional buoy greatly decreases the target density in a high detection range.
environment. This implies that, for a large number of sensors, there should be fewer sensors separated by more distance in the SE and SW quadrants than the NE and NW quadrants.

This simplistic concept is not easily visualized, nor even strictly correct for bistatic systems because of the clustering tendency described in following section, but it is a reasonable guide for understanding and explaining our results. For example, given 8 buoys in the upper left case, only one buoy is needed in each of the SE and SW quadrants, while four buoys are needed in the NW quadrant to equalize marginal return on effort.

CDPs for SCOUT solutions in the inhomogeneous environments are listed at the top of each case in Fig. 1. SCOUT-derived CDPs are significantly higher than those of the circular solutions. For the bistatic target strength cases (upper row), SCOUT achieves CDPs of 0.82 and 0.96, for the 8 and 16-buoy cases, respectively. The corresponding circular pattern results are 0.74 and 0.87. More buoys produce higher CDPs and SCOUT outperforms circles by about 11%. The overall CDP results for a monostatic target strength model (bottom row) are smaller, because the maximum detection ranges are shorter because there is no specular bistatic target strength spike. SCOUT CDPs (0.58 and 0.75 for the 8 and 16-buoy cases) are greater than the circular pattern CDPs (0.48 and 0.66 for the 8 and 16-buoy cases) by 21% for 8 buoys and by 14% for 16 buoys. The greater percentage improvement with fewer buoys is consistent with previous monostatic ship sonar results, where we showed that the greatest optimization gains were achieved when the number of ships or the search time was limited. In other words, when the problem is challenging, like in complicated environments, or with limited assets, or under short search-time constraints, the value of optimization algorithms is enhanced.

BUOY CLUSTERING IN A HOMOGENEOUS ENVIRONMENT
The experiment conducted for this section is decidedly simple. A monostatic detection range of 3.6 nmi is assigned uniformly to all points on a 1 deg by 1 deg grid. Within the grid, a number of monostatic sonobuoys were placed, each of which consisted of a source and a receiver. The source ping times were 0 hr and 10 hr. The acoustics were simplified according to a spherical (20 log(r)) spreading law.

Fig. 2 shows representative SCOUT solutions to the problem. Though their absolute positions changed, their relative positions were nearly constant; the buoys tended to maintain a regular geometry in all four cases, small clusters in which buoy detection ranges overlapped significantly. Indeed, the inhomogeneous case from the previous example also supports this result. The two clusters in the bottom right panel of Fig. 1 are separated by approximately the same relative distance (with respect to monostatic detection range) as the four-buoy case in Fig. 1, i.e., approximately 3.1 detection ranges apart. Thus, from the observations one can conclude that the buoys tend to maintain a “natural” separation from one another, all else being equal. This separation must also be, by virtue of the SCOUT algorithm, a near-optimal solution to the n-buoy placement problem with respect to cumulative detection probability.

Fig. 3 shows monostatic and bistatic results from acoustical modeling of two sonobuoys (each with a source and receiver) 12 nmi apart along a line of latitude in the northeast Pacific. The top panel represents the monostatic probability of detection results for the two buoys scaled between 0 and 1. The bottom panel shows the bistatic results for the same two buoys, operating in pairs. The bottom left panel shows the detection map generated when a receiver at position 1 listens to a source at position 2, while the bottom right panel shows the map generated when a receiver at position 2 listens to a source at position 1. Note that in contrast to the top panel, these two detection results are scaled between 0 and 0.55.
Two things should be noted in these results. First, the bistatic situation, in which the source and receiver are separated, creates an elliptical region of non-zero detection probability around the source/receiver pair. This occurs because acoustic travel time for the target-reflected path (the source-to-target and then target-to-receiver path) must exceed that of the direct blast, i.e., the high-energy acoustic path from the source directly to the receiver. The direct blast suffers no reflection loss and is therefore always louder than and masks any target-reflected path. Therefore, a target-reflected path can only be detected if it arrives after the direct blast, and these paths exist for targets located in an ellipse about the source and receiver points.

Now consider pairs of sonobuoys at various separations, each of which contains a source and receiver, i.e., a simultaneous monostatic and bistatic system. Each of the two receivers in isolation has a monostatic detection pattern like the circular regions shown in the top panel of Fig. 3. In order to maximize the sum of these components, the detection circles should have a minimal degree of overlap. Each of the mixed source/receiver pairs has a bistatic detection pattern like the elliptical regions of Fig. 3. In order to maximize the sum of these components, the buoys should be as close together as possible. Thus, there exists a trade-off between maximizing the detection capability of the monostatic and bistatic components of the system. As the sonobuoys move closer together, gain from the dual monostatic system decreases as the detection circles overlap too much and duplicate effort, while gain from the bistatic system increases. It is this trade-off that SCOUT exploits with multiple bistatic sonobuoys.

The left panel of Fig. 4 shows the total detection area of the two sonobuoys with 50% detection ranges ($R_{50}$) of 2, 4, and 6 nmi, where the total detection area is defined as the area where the combined probability of detection exceeds 0.5. The total detection area increases, and then decreases, as separation distance increases from zero. The red circles show the separation distance chosen by SCOUT in its buoy placement. The SCOUT solutions are nearly identical to the analytical optima. The right panel of Fig. 4 shows corresponding results for a three-buoy group, spaced as an equilateral triangle, (note the larger detection area scale for the 3-buoy case). SCOUT again finds the optimal solutions in all three-buoy cases. A special point about the three-buoy cases and four-buoy cases (not shown) is that the optima occur at a larger separation distance than for the two-buoy case (2.1 times the detection range for two buoys, 2.7 times the detection range for three buoys, 3.0 times the detection range for four buoys). We believe this to also be a result of the geometry of the problem; when three buoys overlap in an equilateral triangle, there is a region of triple circle overlap. This region figures into the calculation of the total detection area differently than the regions of two-circle overlap in the two buoy case. In the end, the total detection area of the three circular detection areas decreases.

Figure 3. Source and receiver pairs in NE Pacific, deep water, 10 ms pulse, $f_c = 500$ Hz, BW = 200 Hz. Top left and bottom right panels put both source and receiver in the same position (monostatic), top right and bottom left panels show them separated by 12 nmi (bistatic).
more quickly than for two circles as separation distance decreases. A similar analysis for four buoys in a square configuration shows that the total detection area decreases even more quickly with separation distance than the three-buoy case.

Figure 4. Total detection area (50% probability) vs separation distance. The detection area reaches a maximum at an intermediate distance. SCOUT results (red circles) yield the optima in all cases.

The above result underscores the value of small buoy clusters in target search problems. Though experiments need to be performed to validate the result in more complicated environments, the value of the cluster may allow future versions of the SCOUT system to restrict the set of all solutions for the buoy placement problem to buoy clusters. This kind of restriction can lead to significant savings in computational time.

SUMMARY AND FUTURE RESEARCH

SCOUT, a search planning system developed for littoral ocean environments, was used to find optimal solutions to a homogenous, multiple sensor problem. The results yielded, consistently, a pattern of sensor clusters, in which a constant, “natural” distance between sensors emerged. These results are consistent with an analytical solution for the maximization of detection area for multiple sensors. We believe these results are important for two reasons. First, the results underscore SCOUT’s value as a coordinator of multiple sensors and as a research tool for the analysis of ASW tactics. Second, the results show that optimal solutions for multiple buoys tend to a small cluster, rather than a sparse grid pattern in deep water.

As noted above, the buoy cluster result requires further study, specifically in complex, inhomogeneous acoustical environments. More generally, the buoy clustering result points to the value of the SCOUT system as a laboratory for tactical evaluation and analysis. The system can be a valuable tool for research because of its ability to analyze a diverse set of acoustical environments and find near-optimal solutions without great computational effort.

In future work, we will perform a more systematic study of the various parameter settings, in a variety of environments. SCOUT appears to be quite robust with respect to most parameters, but near-optimal settings should allow SCOUT to achieve its solutions with less computational effort (fewer generations, smaller populations, etc.). These decisions will be made by an expert system to be developed in future work.