Design and Performance of Irregular Sonobuoy Patterns in Complicated Environments

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Abstract - **Patterns for optimal monostatic sonobuoy fields were developed during the Cold War for use in deep, uniform undersea environments, where a simple median detection range can be used to define a useful fixed spacing between sonobuoys. However, oceanographic and acoustic conditions in the littoral environments where current operations are often conducted are so complex and dynamic that spatial and temporal variability destroys the homogeneous assumption associated with traditional tactical search concepts. Several research efforts have been undertaken to design better placements of passive and monostatic-active sonobuoys, but most of these are evaluation algorithms, as opposed to true planning algorithms. A different algorithmic approach, which begins with a random set of sensor locations and then uses genetic algorithms to find a near-optimal solution, was successfully developed and initially applied to monostatic mobile sensors. The genetic algorithm solutions were non-standard search paths that adapted to complex oceanography, to variable bottom properties, and to assumed target tactics [D.P. Kierstead and D.R. DelBalzo, Military Operations Research Journal (March/April 2003)]. A new capability was then developed to optimize the locations (latitude, longitude, and depth) and ping times of multistatic active sonobuoys in a complex, littoral environment. These algorithms are called SCOUT (Sensor Coordination for Optimal Utilization and Tactics). SCOUT contains two major modifications to the mobile-sensor genetic algorithm approach in order to account for bistatic and multistatic sonobuoy fields, where every receiver is capable of observing data from every source. The first is in structure, where a new chromosome was introduced to describe the tactical plan. It has one gene for each sonobuoy, consisting of a location, an ordered deployment sequence, and a set of ping times. Positions and times in the new chromosome mutate independently and are characterized by an irregular pattern and a non-sequential ping sequence. The second modification is in detection modeling, where a new model for bistatic detection was introduced. It allows for a combination of coherent and incoherent processing. For this work, we postulated that all sonobuoys could be monitored simultaneously. The SCOUT algorithms are an extension of our previous genetic algorithm work and, to the best of our knowledge, they represent the only solution that designs multi-static active sonobuoy placements in complicated environments from scratch, as opposed to recommending general effort allocations or simply evaluating standard patterns with different parameters. This paper discusses the new chromosome structure and simulation results in a realistic environment. The results show the following: a) SCOUT can effectively adapt multistatic sensor fields to the environmental complexity found in littoral areas; b) standard patterns are not optimal even for a homogeneous environment; c) standard patterns are grossly ineffective in inhomogeneous environments where 36-60% improvements in detection performance are achieved with SCOUT; d) 8-16 sonobuoys with SCOUT placement can perform as well as 32 regularly spaced sonobuoys; and e) extra flight time spent on laying irregular patterns is more than compensated by the additional tactical performance achieved.**

I. 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. In other words, they begin with standard, uniformly-spaced patterns, then adjust the fixed spacing between sensors and evaluate the expected performance, usually against a set of possible target trajectories.

The Genetic Range-Dependent Algorithm for Search Planning (GRASP) was developed to support ASW operations in littoral environments [1-3]. The tactical portion of GRASP is the Operational Route Planner (ORP), which uses genetic algorithms to create search paths in complicated environments. As originally implemented, ORP supported passive and monostatic-active mobile sensors. ORP has now been modified to include bistatic active sonobuoys (sources and receivers). We refer to this new capability as SCOUT (Sensor Coordination for Optimal Utilization and Tactics).

The first goal of 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,

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previous experience with multiple-searcher optimization [2] 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.

II. SCOUT CONCEPT

Genetic algorithms are an attempt to find good solutions to difficult problems by mimicking evolution. A simplistic view of evolution is that it depends on five ingredients: a *population* of individuals, each described by a *chromosome*; a *reproductive mechanism*; *mutation*; and *natural selection*. 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 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.

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.

SCOUT uses off-line sensor performance calculations to tabulate signal excess at a grid of points. For a monostatic sensor, signal excess 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 signal excess depends on the full source-target-receiver geometry, which requires a four-dimensional table at each acoustic grid point. For the bistatic application, we rigidly translate the entire source-target-receiver geometry so that the target is at the nearest acoustic grid point, then compute the ranges and azimuths from the target to the source and receiver, and then look up the bistatic signal excess in a four-dimensional table.

The structure of the signal excess file is an original innovation that exploits properties of ORP. We chose to structure the bistatic signal excess file about the target, rather than the source or receiver, because the primary contribution to bistatic signal excess is the source-to-target-to-receiver transmission path. The source-receiver geometry affects the signal excess calculation through direct-blast masking and reverberation. We calculate direct-blast masking internally from geometric analysis. Reverberation is much less sensitive to the precise source-receiver geometry than signal excess 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 signal excess data that must be computed.

III. RESULTS FOR INHOMOGENEOUS ENVIRONMENT

In the first example, Fig. 1, oceanographic and acoustic conditions vary across the search region. We 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. In each, we have: a) 1 deg × 1 deg total search region; b) 6-hr search duration; c) sonobuoy field laid prior to the start of search; and d) 5-kt target on random patrol 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. Each buoy is a source, that "pings" twice, and a receiver with vertical aperture. Solutions for bistatic and omni-directional target strength are shown in the top and bottom rows, respectively. The white disks are the SCOUT solutions, while the connected gray dots represent the best possible (highest CDP) circular pattern, which is a common tactic.

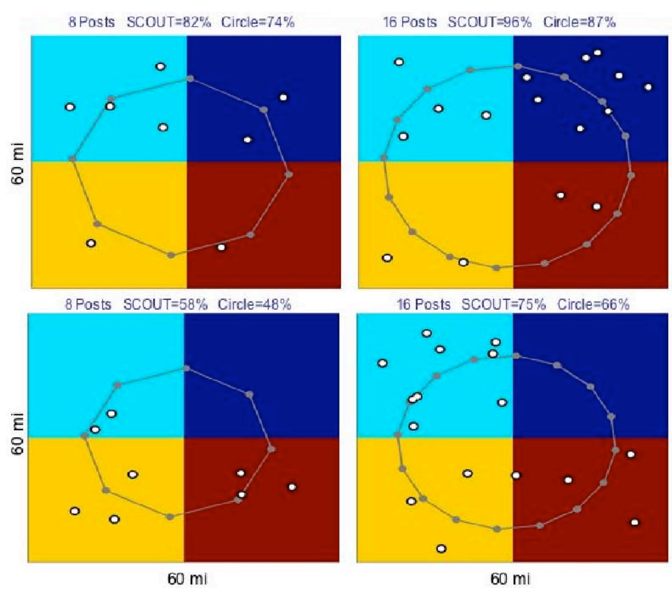

Figure 1. SCOUT optimized patterns (white disks) and best circular patterns (connected gray dots) in inhomogeneous environments for 8 buoys (left), 16 buoys (right), bistatic target strength (upper), and omni-directional target strength (lower).

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. This simplistic concept is not easily visualized, nor even strictly correct for bistatic systems but it is a reasonable guide for understanding and explaining our results. For example, given 8 buoys in the upper left case of Fig. 1, 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 82% and 96%, for the 8 and 16-buoy cases, respectively. The corresponding circular pattern results are 74% and 87%. Doubling the number of buoys increases CDPs and SCOUT outperforms circles by about 11%. The overall CDP results for a bistatic target strength model (upper row) are larger than for the monostatic target strength case (lower row) because the bistatic target strength model contains a large specular reflection spike that increases detection range under certain geometries. SCOUT CDPs (58% and 75% for the 8 and 16-buoy cases) are greater than the circular pattern CDPs (48% and 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.

The next example, Fig.2, shows a comparison between a SCOUT monostatic solution (dots connected by lines) and a standard 3-2-3 staggered pattern (Xs) for 8 passive buoys. The colored background shows an artificial detection range map (red is 1.6 nmi and blue is 0.6 nmi) in a 60 x 60 nmi search area. The CDP results for an 8-hr search are 73% and 61% for SCOUT and staggered, respectively. The lower CDP for the staggered pattern results from the regular spacing which causes some buoys to be in good (red) areas and some to be in worse (blue) areas. All of the SCOUT positions are in yellow to red areas.

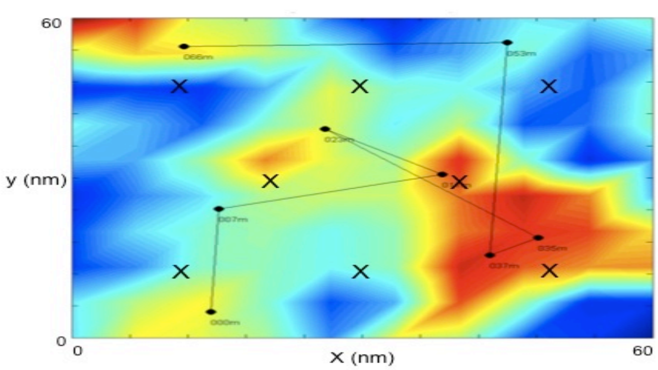

Figure 2. SCOUT solution (dots) and a staggered grid (X's). Colors represent detection range (0.6 – 1.6 nmi for blue to red, respectively).

A full multi-static active solution is shown in Fig. 3 for 16 buoys (upper row) and 32 buoys (lower row). As in the Fig. 1 example, each buoy is a source-receiver pair (the source "pings" twice during the search period and the receiver has vertical aperture) and the target is on random patrol at 5 kt. The left column shows a staggered pattern and the right column shows the SCOUT solution. For this example, the underlying colors represent bathymetry in the Sea of Japan. The shallowest areas (< 200 m) to the West are in red and the deeper areas (approximately 2000 m) to the East are in blue. The scenario is an 8-hr search during September.

There is a remarkable improvement in CDP when using the optimized SCOUT pattern. For 16 buoys the CDPs are 22% and 65% for the staggered and SCOUT patterns, respectively. Notice that there are about 10 buoys in the shallow-water areas shown by yellow and red for both staggered and SCOUT and that there are about 6 buoys in the deeper-water (blue) areas in both cases. The three-fold increase in CDP is caused by a combination of grouping, or clustering, of the buoys, and their positions – note the "sweet spot" in the southwest where SCOUT places 3 buoys. We know from many other calculations that the relative positions of buoy pairs and triplets can be the most dominant part of the solution. There is also a significant improvement in the 32-buoy case. The CDPs are 45% and 72% for the staggered and SCOUT solutions, respectively. Again note the set of SCOUT buoys in the southwest area.

In the Fig. 3 examples, we note that the SCOUT patterns do not appear to sample, or "cover" the entire search region when compared to the regular staggered patterns. Instead, SCOUT buoys tend to cluster together in the best search areas, leaving large, apparently unsampled regions. This strategy may seem counter-intuitive, especially when judged by area "covered", but when the goal is to maximize CDP against moving targets, the non-standard, optimized approach can be superior.

Several other cases were examined and the composite results are shown in Fig. 4 for two months (September and February), for 8, 16, 24, and 32 buoy patterns, and 3 examples with 5 pings. There are two ways to describe the improvement associated with optimization: first by CDP gain and second by reduced effort or resources. For example, during September with 2 "pings" per buoy, the CDP for SCOUT exceeds that of the staggered pattern by 60% for the 32- buoy case and there is a 4:1 reduction in buoys needed to achieve a CDP of 45%; *i.e.*, 8 optimized buoys achieve the same CDP as 32 staggered buoys. In addition, note the diminishing return in optimized CDP. In this case the marginal gain is significant when moving from 8 to 16 to 24 buoys (46% to 65% to 72%), but CDP improves by only 1% when moving from 24 to 32 buoys

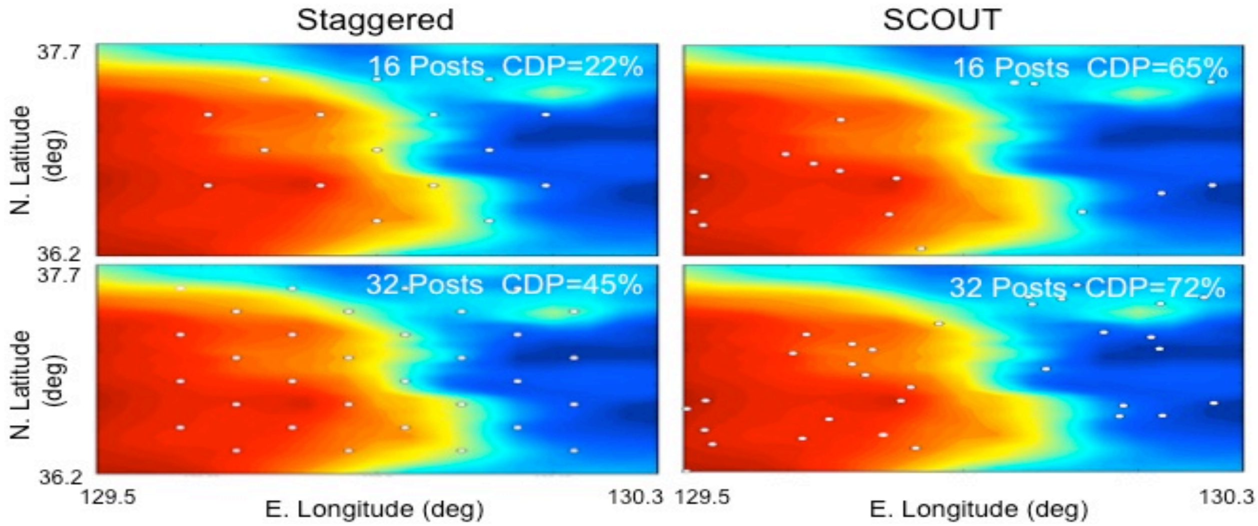

Figure 3. SCOUT (right) vs. staggered (left) buoy patterns for 16 (upper) and 32 (lower) buoy cases. The background is bathymetry (shallow <200m in red and deep 1000-2000 m in blue) in the Sea of Japan.

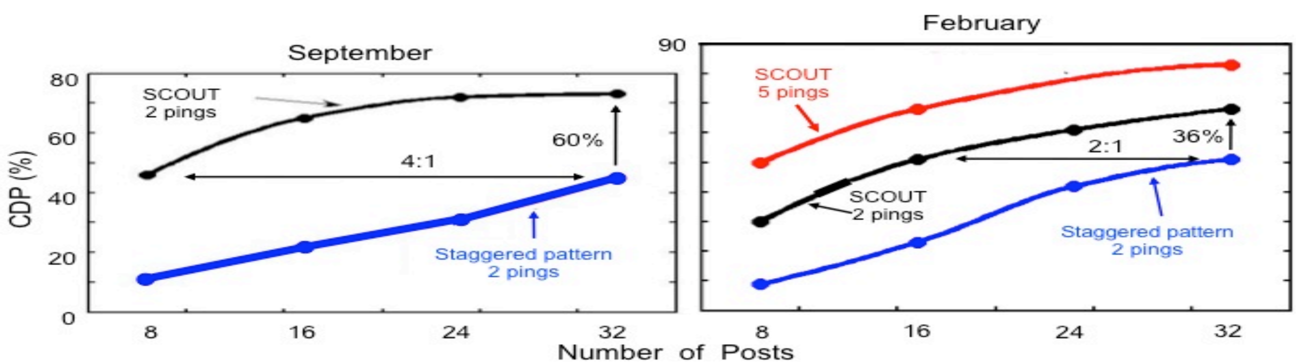

Figure 4. Comparison of CDP performance for staggered (blue) and SCOUT (black) optimized buoy patterns for September and February.

72% to 73%). SCOUT allows the tactical planner to control buoy deployments and save resources (fewer buoys and reduced deployment time), while maximizing performance.

Similarly, during February with 2 "pings" the CDP for SCOUT exceeds that of the staggered pattern by 36% for the 32- buoy case and there is a 2:1 reduction in buoys needed to achieve a CDP of 50%; *i.e.,* 16 optimized buoys achieve the same CDP as 32 staggered buoys. Finally, the effect of extra "pings" is shown with the February results.

IV. SUMMARY

SCOUT, a search planning system developed for littoral ocean environments, was used to find optimal solutions for multi-static active sonobuoys in simulated non-homogeneous areas. We show that optimized patterns can outperform standard patterns by significant amounts. We believe these results underscore SCOUT's value as a coordinator of multiple sensors and as a research tool for the analysis of ASW tactics. The results also show that optimal solutions for multiple buoys allow control of resources while preserving, and maximizing performance. 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.

ACKNOWLEDGMENT

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