Submarine tracking using multi-sensor fusion and reactive planning for the positioning of passive sonobuoys

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Abstract

This paper describes the development and validation of a simulation model capable of simulating a submarine hunt using multi-sensor fusion of signals from passive sonobuoys and of computing a near-optimal placement for the next buoy to be deployed.

Keywords: *passive sonobuoys, archipelagic anti-submarine warfare, submarine tracking, reactive planning, Kalman filter*

1 Introduction

The overall objective of this research is to determine the possible benefits of applying reactive planning and multi-sensor fusion to the problem of determining and tracking the position of a submarine in archipelagic anti-submarine warfare (AASW). In this paper, we discuss the use of such methods in a simplified gaming scenario: a single target moving along a predetermined two-dimensional path is to be tracked for as long time as possible, given a limited supply of sonobuoys and a prespecified tracking performance.

During the game, either the player or the simulator itself may place sonobuoys at arbitrary locations within the gaming area. The information acquired from the sonobuoys is used to calculate the position of the submarine, using the *generalized hyperbolic fix method* [2][7]. The signal-to-noise ratios at the positions of the sonobuoys is calculated by use of the *sonar equation* [3][8] and compared against a detection threshold. The sonobuoy position and timing uncertainties are taken into account when computing an elliptical confidence region depicting the probable location of the sub.

Effective target tracking required the development of a *Kalman filter-based prediction method* [1][5][8] for the near future position of the target. The filter contains a model of the dynamics of a “generic” submarine. To bring about *efficient automatic buoy deployment* an optimization algorithm was designed and implemented [8].

To make the model relevant to the solution of the practical problem, realistic values for problem parameters have to be used. Such parameters include the minimum time from first detection to first effective buoy deployment; the sensor detection ranges; the relation between speed and sound emission from the sub; the minimum signal integration time to achieve acceptable signal-to-noise ratios; and uncertainty estimates for buoy locations and time differences of arrivals.

For practical application it is important that the proposed technique can be used also in disturbed conditions such as presence of intense surface traffic, multiple targets, bad weather conditions, etc. This study does not address these issues explicitly.

A literature search was made to find previous results concerning the combined use of passive sonobuoys, data fusion, and tracking. A few articles were found but none of them deals with the problem of reactive planning for the positioning of buoys.

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2 A Simulation Model for Submarine Position Estimation from Sonobuoy Signals

To evaluate the proposed tracking scheme, an interactive simulation model was developed [7], allowing different buoy deployment tactics to be studied. In each time step of the discrete simulation the signal-to-noise ratio at the locations of the sonobuoys is computed; if the ratio is above a predetermined detection threshold, and if the required integration time has been reached, the information from that sonobuoy is taken into account. Next, the time differences of arrivals of the sound reaching the hearing sonobuoys are computed. Using this information, the most likely position and an associated confidence region may be found and displayed.

2.1 The submarine model

The submarine follows a predefined polygonal path. The submarine may pause for a predefined time interval at a given point. The submarine's entry into the gaming area is followed by a first detection which is being announced to the player. The sound level of the submarine is represented as a tabulated piecewise linear function of its speed.

2.2 Properties of sonobuoys

The advantages of using passive sonobuoys instead of other acoustic measuring systems are: they are cheap; they can be deployed quickly at an arbitrary position; they are passive and do not reveal themselves acoustically to the submarine; they are not disturbed by noise from a platform.

The modelled technique requires precise position data for the sonobuoys to be able to locate the submarine accurately. Such position data could be obtained in several ways, including the use of fixed acoustic beacons and DGPS receivers in the buoys.

Current sonobuoy designs have a limited lifetime, at most a few hours. In AASW, the submarine may lay silent on the sea-floor for several days if necessary. Thus, with current sonobuoy design, the operator has to expend, say, three buoys every third hour, just to keep the silent submarine from escaping.

2.3 Modelling sonobuoys

In our model, sonobuoys can not be retrieved for reuse. The integration time is modelled by disregarding the information from a particular buoy for a suitable number of time steps (see below). The deployment time is modelled as the sum of the activation time and the delivery time.The activation time is a constant and the delivery time is dependent on the distance between the current position of the buoy delivery platform and the intended position for the next sonobuoy.

2.4 Detection threshold

DT is a measure of the minimum sound level at the buoy required to detect the signal. A modern submarine does not generate narrowband sound signals so the broad-band detection threshold has to be used. We cite from [3] the relation: $DT = 5\log d - 5\log T\beta$

Here T denotes the integration time of the signal, d is the signal-to-noise ratio and β is the bandwidth. If T is set too short a detection is not possible and if it is too long tracking is not possible. To determine d we have to decide values of P_{fa}, the false alarm probability, and of P_D, the detection probability. The corresponding value of d can then be obtained from the ROC curve (see [3]). We have chosen $P_{fa} = 0.0001$, $P_D = 0.99$, $\beta = 1000$ Hz and $T = 4$ sec. We get $d = 36$ and finally, $DT = -10$ dB.

2.5 The Generalized Hyperbolic Fix Method

The *Hyperbolic Fix Method* is commonly used to calculate the positions of underwater targets, detected by passive sonobuoys. It is based on measurements of the time differences between arrivals (TDOA's) of the sound travelling from the target to each sonobuoy. This time difference can be estimated by computing the time difference which maximizes the cross-correlation between time-domain sound pattern windows for each pair of buoys. Using this estimate, a system of equations can be set up whose solution is an estimate of the unknown position of the target.

To use this method, it is necessary that at least three sonobuoys hear the target simultaneously. When more than three sonobuoys hear the target, a linear, overdetermined system of equations can be formed. This system can be solved using a standard least squares method. We will call this technique the *Generalized Hyperbolic Fix Method* [2][7].

2.6 Uncertainty Ellipse Computation

The least squares solution for the position of the target provides an estimate of the mean value of the statistical distribution for the submarine's position. To model also the variance, or mean square error, of the target's position both the sonobuoy positions and the time differences of arrival need to be represented as Gaussian-distributed stochastic variables with zero mean. For a derivation of the parameters of the uncertainty ellipse the reader is referred to [2] and [7].

2.7 Predicting the Position of the Submarine

The buoy configuration delivers a position estimate and the uncertainty of this estimate for every time step. To reduce this uncertainty and to enable the motion of the submarine to be predicted, a Kalman filter was developed which delivers a minimum-variance weighted average of the current measurement and the predicted position, computed from previous measurements and a simple model of target dynamics.

The only target dynamics parameters which need to be provided are the variances of the acceleration components σ_p^2 and σ_n^2. For a single-propeller ship the practical maximum values of the acceleration components have been assumed to be a_p=0.02 m/s^2 and a_n=0.04 m/s^2. By choosing the variances equal to a_p^2 and a_n^2 accurate tracking is possible during realistic manoeuvres.

3 The Buoy Deployment Problem

To detect a submarine, the buoys must be dropped into the water soon after the first alarm of the presence of a possible target. Other timing factors are the deployment time (required to deploy and activate a buoy at a certain position) and the sonobuoy lifetime.

3.1 Estimation of the buoy range

Both when estimating the uncertainty in a future position estimation of the target and when calculating an optimal buoy position, an estimate of the hearing range is needed. This range, which should be estimated as accurately as possible, is dependent on the speed and type of the target and on the sea conditions. It can vary from close to one hundred meters for an ultra silent modern submarine in bad weather up to many kilometers when conditions are ideal.

3.2 Optimization of Buoy Placement

An algorithm was developed which computes a near optimal placement of the sonobuoys. The decision of buoy deployment can be split in two, one which determines the point in time when a new buoy must be deployed, and one which determines the most favourable position for this buoy.

Using the Kalman filter, the future position of the submarine is predicted for every time step t. This gives us a confidence ellipse within which the submarine will be located with probability p at time $t+T$. Now, wherever in this ellipse the submarine may be, we want to be able to measure its position with an error less than δ. If this is possible there is no need to deploy another buoy, but if the measurement error grows too large for some location of the target at time $t+T$, we will have to deploy a new buoy.

In every simulation step we want to gain as much information as possible from the buoy constellation. Therefore the position for the next buoy deployment should satisfy two requirements:

- there should be no other buoy position which would enable the buoy constellation to add more information in the next time step, for every future target position within the predicted area
- in order to save buoys, the position should be chosen so that the buoy can be of use for as long as possible.

These requirements are in conflict and a balance between them has to be found. We refer the reader to [8] for a discussion of how this conflict can be resolved.

3.3 Regaining contact

The game will start by displaying an approximate position for an observation of the submarine. At the later time when tracking is to start, the distance travelled by the submarine since the first observation can be calculated from an estimate of its speed. This is unknown but presumably slow since the submarine will be operating under sound emission limitations. On a circle with radius equal to the estimated travel distance around the original observation buoys are deployed until one of them indicates a detection. Around this buoy a few more are deployed so as to get at least four hearing buoys. If no detection occurs the procedure is repeated after doubling the speed estimate.

4 Conclusions

We have developed a simplified two dimensional model without islands and sea-floor structure and *all conclusions below are related to the model and not to reality.*

Thus, in the model's world it is possible to track a hostile submarine with passive sonobuoys; with four or more sonobuoys in suitable positions, the submarine's position can be estimated and a confidence ellipse for this position can be calculated; from a generic Kalman filter not only a prediction of the motion is obtained, but also a reduction of the position uncertainty; the more one knows about the dynamic properties of the target the larger reduction can be obtained; based on estimates of the uncertainty of future measurements one can position the buoy in a suitable way; the critical aspect of the simulation is the length of the time period from the initial observation until contact has been regained.

The methods and parameters were validated as follows: by discussing with submarine and signal processing experts the choice of parameters for modelling the submarine and the sensor measurements; by applying standard statistical tests to the Kalman-filtered measurements; by comparing the optimizer's result with that of a closed solution in an idealized situation; and by studying in detail the behavior of the objective function during several test runs.

In the model, the sound reaches the sonobuoys by a straight-line route. Although this is a strong simplification of reality, we defend it by referring to the fact that in our concept the distance between target and sensor is far shorter than is usually assumed in sonar detection models, a few hundred meters or even less. This characteristic should make reverberation and interference effects manageable.

When tracking those very silent submarines which may be deployed in the future, the distances between buoys and target may need to be so small that the target can no longer be represented by a point-like sound emitter. It is not obvious that the technique can be extended to handle this case.

On the other hand, delivery platform, sensor, energy source, and communication system developments will probably allow precision deployment and networking of large numbers of very small and cheap measurement devices in the future.

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