

Using Environmental Models to Optimize Sensor Placement

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Abstract—Sensors used in protective applications are conventionally placed on perimeters or over areas in an evenly distributed pattern. However, such patterns may actually be suboptimal, since environmental factors may make some forms of attack more or less likely than others. We describe a protective application of sensors for detecting underwater threats in an urban estuary environment. We demonstrate that environmental information, derived from a computational river current model, can be utilized to optimize sensor placement, increasing detection rates and decreasing the number of required sensors. Simulation results show a significant improvement in detection likelihood for a given number of sensors; alternatively, fewer sensors can be used while still maintaining the detection rate of a conventional approach.

Index Terms—Diver detection, environmental modeling, harbor security, port security, sensor optimization, sensor placement.

I. INTRODUCTION

DETECTING and tracking moving objects is difficult. Sensory data and other information are often sparse or incomplete and are always associated with a degree of uncertainty [1] which may, itself, be hard to estimate.

Sometimes it is possible to incorporate additional information into decision making by combining prior knowledge of the environment in which the object is moving with a statistical model of the object's behavior in response to that environment. In [2], mobility and terrain analysis are used to predict possible movement plans for targets.

An interesting example is the case of detecting and tracking intentionally moving objects in a river, since rivers contain distinctive and varying currents which impose constraints on the objects' motion. Current data can be derived from a computational estuarine model [3].

Our previous work has explored different configurations of both moving, [4], and stationary, [5], sensors. To our knowledge, no previous work considers the effects of current speeds on intentionally moving objects, and in turn how sensor networks should be designed to take advantage of those effects.

II. PROBABILITY OF DETECTION

We consider the case of detecting a diver who crosses a linear arrangement of sensors stretched across a river. In particular,

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we consider the case of a diver swimming south in the Hudson river against northbound currents. We denote the conditional probability that the i^{th} sensor will detect the diver, given that he crosses the line of sensors at a particular point x by $P(D^i|x)$. Assuming that the performance of each sensor is independent of the others, it is easy to show that the total probability that a diver, crossing at point x , be detected by the entire set of sensors is given by

$$P(D^T|x) = 1 - P(\overline{D}^T|x) = 1 - \prod_i \{1 - P(D^i|x)\}. \quad (1)$$

The terms, $P(D^i|x)$, are calculated using a simple sensor model in which probability of detection is approximated by a linear decrease with range from a maximum value of 95% to reflect the fact that detection is never guaranteed. This model is based on recent work on passive diver detection [6], which suggests that divers can be detected by thresholding a feature value derived from a passive acoustic hydrophone signal. Note that the technique described here can accommodate any detection versus range sensor model. Hence, we can define

$$P(D^i|x) = 0.95 \left(1 - \frac{|x - x_i|}{50}\right), \quad 0 \leq |x - x_i| < 50 \quad (2)$$

where x_i denotes the position of the sensor and the maximum detection range is 50 m. We now examine the joint probability that a diver chooses to cross the line of sensors at a particular point x and is detected when he does, so

$$P(D^T, x) = P(x)P(D^T|x) = P(D^T|x)p(x)\delta x \quad (3)$$

where $p(x)$ is the probability density function which describes the likelihood that locations x along the sensor line will be the site of an attempted crossing by the diver. The term $p(x)$ is defined by a "diver preference" curve, a simple function of current speed based on advice from our expert divers. We use a log-normal distribution to reflect the fact that it is impossible for the diver to swim against currents beyond 0.5 ms^{-1} (treated as negative current speeds), and also that the diver will not wish to travel at very high speeds (with the current) in the highly turbid and cluttered river environment. In contrast, a conventional Gaussian distribution is not able to model zero probabilities for large negative current speeds. Hence

$$p(x) = f(v_x) = \frac{1}{(v_x + 0.5)\sigma\sqrt{2\pi}} e^{-\{\ln(v_x+0.5)-\mu\}^2/2\sigma^2} \quad (4)$$

where the river current speed (v_x) at location x is found from the current profile data output by our computational estuarine model [3]. This model forecasts current speeds for locations on a grid of cells, spanning the lower Hudson river and New York harbor. We generate the current curve $v_x = f(x)$ by least-squares fitting a polynomial to current values forecast for a line of cells across the river (Fig. 1). We can now evaluate the effectiveness

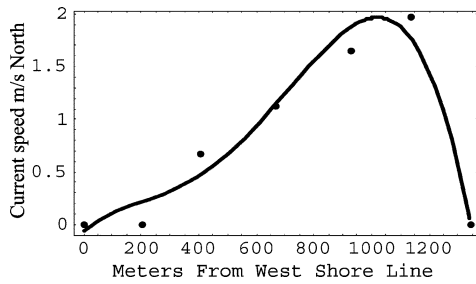


Fig. 1. Current speeds for cross section of Hudson river. Polynomial interpolation of forecast current speeds from the NYHOPS computational estuarine model.

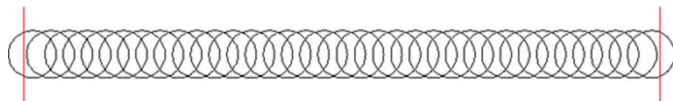


Fig. 2. Conventional arrangement of 35 sensors across a 1340-m wide river. Circles represent perimeter of sensor coverage; vertical lines denote river banks. Probability of detection = 0.869.

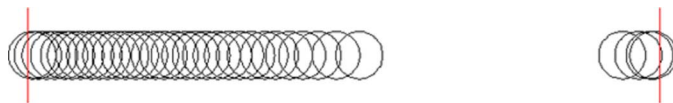


Fig. 3. Improved arrangement of 35 sensors, optimized using environmental modeling. Probability of detection = 0.971.

of any particular arrangement of sensor placements as the total probability that a diver will be detected, should he attempt to cross the sensor line, found by integrating (3) across the river

$$P(D^T) = \int_{\text{East_bank}}^{\text{West_bank}} P(D^T)p(x).dx. \quad (5)$$

III. RESULTS

Using (5) as a fitness function, we can use a standard non-linear optimization procedure to optimize the positions of a set of sensors. If 35 sensors are positioned in a conventional, equi-spaced linear pattern (Fig. 2), (4) yields a total probability of detection, $P(D^T)$ of 0.869. In contrast, when we use our computational estuarine current model in conjunction with the diver preference curve, to optimize sensor placement (Fig. 3), we attain a significantly improved total probability of detection of 0.971. Effectively, we have improved detection rates by removing sensors from regions of current that are impossible for a diver to navigate, and utilizing those sensors in more vulnerable parts of the river. Conversely, for a conventional sensor arrangement to achieve the same detection rate of 97% would require 58 sensors, so environmental optimization has achieved a 40% saving

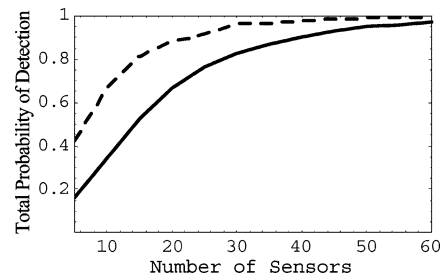


Fig. 4. Variation in total probability of detection with number of sensors. Top dashed line represents environmental optimization. Bottom solid line represents conventional equi-spaced arrangement.

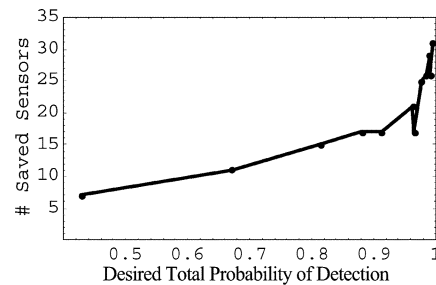


Fig. 5. Number of sensors saved using environmental optimization, while maintaining same detection rate as conventional arrangement, for various levels of desired detection rate.

in the number of required sensors. Fig. 4 shows how the benefits of environmental optimization vary with the total number of sensors. Fig. 5 shows the number of sensors which can be saved by utilizing the environmental optimization procedure, while maintaining the same detection rate as a conventional arrangement.

IV. FUTURE WORK

Future work will extend this technique to detection in 2-D and 3-D spaces, examine control rules for mobile sensors in response to varying real-time current information, and may investigate the use of salinity forecast models for optimizing acoustic sensor placement.

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