Terrain Mapping With Forward Looking Sonar on Unmanned Underwater Vehicles

Michael R. Medeiros and Robert N. Carpenter
Naval Undersea Warfare Center
1176 Howell Street
Newport, Rhode Island 02841-1708, USA
medeiromr@tech.npt.nuwc.navy.mil carpenterrn@tech.npt.nuwc.navy.mil

Abstract

In the future, successful reconnaissance operations conducted in shallow water with Autonomous Underwater Vehicles will rely heavily on a high performance, high resolution, forward looking sonar coupled with terrain mapping algorithms for object detection, localization and classification, sea bottom mapping and feature extraction. This paper describes in detail a terrain mapping algorithm based on an advanced forward look sonar design. The development is illustrated with in-water results.

1. Introduction

In the future, successful reconnaissance operations conducted in shallow water with Autonomous Underwater Vehicles (AUVs) will rely heavily on a high performance, high resolution, forward looking sonar (FLS). These mission functions include object detection, localization and classification (DLC), sea bottom mapping and feature extraction for navigation guidance and control (NG&C) and obstacle avoidance. For several years, the U.S. Navy's Advanced Systems Technology Office (ASTO) and Office of Naval Research (ONR) have sponsored the development of NUWC's high resolution array (HRA). The HRA is a planar array designed for operation in a 21-inch diameter vehicle. Its current design consists of half-wavelength elements of 1-3 composite material configured in a 20 wavelength circular aperture. Recently, NUWC has embarked on the development of algorithms that rely on the wide transmit coverage and narrow receive beams of the HRA to provide images of seabed topography, objects on the bottom and objects in the volume. This paper focuses on two aspects of this effort: a terrain mapping algorithm and the small object localization performance of the HRA. The paper is organized as follows. First, a brief system description of the HRA will be given. Next, the terrain mapping algorithm will be discussed in detail and will include processed results from in-water data collected with the HRA. Finally, theoretical bounds on the variance of target angle estimates made with the HRA will be reviewed and compared with in-water results.

2. HRA Overview

The HRA is a forward looking planar array designed for operation in a 21-inch diameter vehicle. It has evolved from a prototype 40x40 receive-only array constructed from polyvinylidene fluoride (PVDF) [1] to its current design consisting of 1272 half-wavelength elements of 1-3 composite material (PZT-5H) configured in a 20 wavelength circular aperture (design frequency of 87 kHz) [2]. A subset of the elements consisting of two rows of 32 elements each are chosen to provide single ping transmit coverage of approximately 80 degrees in azimuth by 40 degrees in elevation with a source level of 210 dB. Wide angle azimuthal transmit coverage is achieved by means of element phase shading. Receive beams are formed from a subset of 511 of the remaining 1208 elements. These elements were chosen and fixed during the design process to yield the lowest peak sidelobe level (Â 20 dB down from the peak mainlobe level) while constraining the mainlobe to be approximately three degrees wide for beams steered over the transmit coverage region [3].
3. Terrain mapping algorithm

The terrain mapping algorithm is designed to provide single ping, wide swath seabed topographic data from FLS's. In this section, a detailed description of the functional flow of the algorithm is presented. In order to best illustrate the various steps of the algorithm, a series of intermediate results based on a set of in-water test data collected with the HRA will be presented.

3.1 Test data description

The HRA was deployed at a 9 meter depth in 21 meters of water (nominally). The array was mounted on a panning mechanism at the end of an elevator of the Gould Island Test Facility, located in Narragansett Bay, Rhode Island. A sidescan sonar map of the area is shown in Figure 1. The test area is characterized as a nearly flat, silt bottom bowl, with a seven meter high, curved rim to the south and east of the facility. The rim is clearly evident along the bottom and right-hand sides of the sidescan image. The elevator with the panning mechanism and the array are located at the northeast corner of the pier complex seen near the lower left-hand corner of the figure. The origin of the coordinate system is centered on the array. The array was mechanically panned so that its ±40° transmit beam was directed towards the rim and a 10 mS, 3000 Hz linear stepped FM waveform was transmitted. The mapping coverage is depicted as the solid white lines emanating from the elevator. To better illustrate the terrain mapping algorithm, detailed results will be presented along a single scan line, indicated by the dashed line in Figure 1, as well as the entire single-ping map subtended by the solid lines.

![Figure 1: Sidescan sonar image of the Gould Island test area.](image)

3.2 Algorithm functional description

The functional flow diagram is shown in Figure 2. Each numbered functional block will be detailed separately and example results presented where appropriate.
1. Read Data Sample: A single, complex-valued data sample is retrieved from each receive element. All system gains are removed so that incoming data values represent pressure at the face of the array (re 1 μPa).
3. Shade: Two-dimensional Chebyshev weights are applied to the data.
4. Horizontal Steer: Complex phase delays are applied to each element (511 elements) to steer the array to a given azimuth. The elements in each row are then summed to form horizontal staves.
5. Vertical Beamform: 256 vertical beams are formed via FFT and beam powers are computed. Figure 3 depicts an example vertical beam scan, steered horizontally to the dashed line in Figure 1. The sonar array is located at 0 meters range and 0° vertical angle. Positive valued vertical angles are down. The echo from the bottom is clearly seen starting roughly 45° below the sonar. A small bump is evident in this bottom echo trace at a range of 120 meters from the sonar. This bump is due to a portion of the rim at the test site. Note that Figure 3 shows the vertical beam powers for an entire ping receive cycle (many consecutive time samples), and that the method presented here operates systolically (one sample at a time), the entire beamscan is presented for clarity. This convention will be used in other illustrations.
6. Find Detections: For each time slice, the average beam power across the 256 vertical beams is computed. Detections are defined as those beams with power exceeding the average by 6 dB. Figure 4 shows those beams from the vertical scan that exceed the threshold. Next, in order to determine target directions, detection peaks are found from beams whose power is larger than that of their immediate neighbors. Figure 5 illustrates detection peak localization at a range of 120 meters from the sonar. The rim (at +5°) and a reflection of the bottom off of the surface (at -10°) are the sources of the two detection peaks shown in the figure.
7. Refine Detections: The raw detection peak powers are refined by fitting, via least squares, a parabola to the peak and the two values on either side of the peak.
8. Store Detections: The refined angles are accumulated into 512 equal angular vertical bins (spanning ±90°). Only the maximum power response is maintained in each angular bin, together with its corresponding refined angle and sample number. Steps 1 through 8 are repeated until all received data samples from a sonar transmit cycle have been stored into the 512 equal angular vertical bins, this concludes systolic operation. Figure 6 depicts the stored refined bottom detection angles versus range, overlaid on top of the set of detections from Figure 4. The bottom profile is cluttered with outliers caused by noise (volume reverberation and sidelobe returns). The post-systolic filtering performed in steps 9 through 13 reject clutter from the raw bottom profile.
9. Reject Noise: A nine sample moving average filter is run along the stored power estimates, starting from the maximum stored downward angle and proceeding to the minimum stored angle. If the power of the point under inspection is more than 10 dB lower than the mean power, the point is considered noise and rejected from the profile. Figure 7 illustrates the bottom profile after noise rejection.
10. Convert to Cartesian: The stored, noise rejected, bottom profile is converted from vertical angle versus sample number to depth versus horizontal range, and the overall slope of the bottom profile is determined (via a linear fit) for later use in slope rejection. Two methods have been employed to perform this conversion. One is based on straight-line propagation and one is based on ray theory. The sound speed profile at the test site was nearly isovelocity; therefore, the straight-line propagation conversion method was used. Figure 9 displays the bottom profile after conversion to depth below the sonar versus horizontal range.

11. Reject Spikes: The converted bottom profile presented in Figure 9 shows a nearly flat bottom 12 meters below the sonar. Clearly seen is a portion of the rim 120 meters away from the sonar. This profile is contaminated by single sample spikes due to volume reverberation (spikes point toward the sonar) and sidelobe noise (spikes point away from the sonar). Noise spikes are especially prevalent in the area close to, and almost directly under, the sonar, where the transmit beam is weak. Spike removal is accomplished by running a six sample comparative filter (three samples before and after the point under inspection) along the profile displayed in Figure 9. If the horizontal range to the point under inspection is greater than, or less than that of its six immediate neighbors, the point is rejected as a spike. Figure 10 shows the example bottom profile after spike removal.
12. Reject Slope: The point-to-point slope is computed between each pair of points in the bottom profile. If the slope differs from the overall slope (step 10) by more than 60°, the rejection flag is set. If the slope differs from the overall slope by more than 30°, the profile is examined for an upward or downward trend. If a directional trend exists, points are allowed to pass (up to the 60° point-to-point slope limit), otherwise, the rejection flag is set. If the rejection flag has been set, the current depth point and the previous 9 depth points are averaged, and the point furthest from the mean is rejected from the profile. The example bottom profile after slope rejection is presented in Figure 11.

13. Smooth: A three sample moving average filter smooths the bottom profile (Figure 12). This concludes the processing of one azimuth.

14. Change Azimuth: The azimuthal steering angle is incremented, and steps 1 through 13 are repeated until all desired azimuth angles are processed. The HRA has a ±40° horizontal transmit beam, and a 3° wide receive beam. Processing azimuth angles from -40° to +40° in 2° increments covers the transmit angular swath with adequate spacing to minimize scalloping loss. An entire single ping, forward-looking terrain map is presented in Figure 13 in which a large section of the test area rim is clearly seen. The corresponding echo level (previously referred to as beam power) map is shown in Figure 14. Note the rise in backscatter levels due to the face of the rim, and the fall in backscatter levels as the range from the sonar increases. This drop in echo level versus range is expected and is caused by transmission loss and decreasing grazing angle versus range from the sonar (assuming a flat bottom). Details on multiple ping map construction can be found in [4].
Figure 7: Example bottom profile after noise rejection.

Figure 9: Example bottom profile converted to rectangular coordinates.

Figure 10: Example bottom profile after spike removal.
Figure 11: Example bottom profile after slope rejection.

Figure 12: Example bottom profile after smoothing.

Figure 13: Example single ping bathymetric map.
4. HRA angle estimation accuracy

In addition to terrain mapping, the HRA is ideally suited for detecting and localizing small objects. The theoretical detection performance of the HRA can be found in [5] and a detailed development of the theoretical bounds on target position can be found in [6]. In this section, a brief review of those bounds will be given and compared with in-water results taken against small spherical targets. The geometry of interest is shown in Figure 15 where the array is located in the x-y plane and the point target of interest is located at \( x, y, z, (r, \theta, \psi) \). Given the return from an arbitrary transmit signal \( s(n), n = 0,1,\ldots,N-1 \) (baseband samples), the Cramer-Rao bound on the variance of any unbiased estimator of \( \theta \) can be calculated as follows (note that for values of \( \psi = 0 \) or \( \pi, \theta \) represents azimuth angle). Let \( SNR_{\theta} \) denote the array output signal-to-noise-ratio due to the point target. Define the mean square bandwidth of the signal as

\[
MSB = \frac{\sum_{k=0}^{N-1} |\tilde{S}(k)|^2}{\sum_{k=0}^{N-1} |\tilde{S}(k)|^2},
\]

where \( \tilde{S}(k) \) is the \( k^{th} \) DFT coefficient of basebanded signal and \( \omega = \frac{2\pi k B}{N} \), with \( B \) the bandwidth of the waveform. Also, define the mean square aperture function of the array as

\[
MSA = \frac{\sum_{m=1}^{M} \left( \frac{x_m}{c} \right)^2 |A(m)|^2}{\sum_{m=1}^{M} |A(m)|^2},
\]

where \( x_m \) is the \( x \) value of the \( m^{th} \) element in the array (the array is assumed to have mirror symmetry about the \( x \) and \( y \) axes), \( A(m) \) is the amplitude of the \( m^{th} \) element and \( c \) is the speed of sound. The Cramer-Rao bound for any unbiased estimator \( \hat{\theta} \) of \( \theta \) is

\[
\text{var}(\hat{\theta}) \geq \left( \frac{2SNR_{\theta} MSA(\omega_0^2 + MSB)\cos^2 \theta}{} \right),
\]

where \( \omega_0 \) is a measure of the center frequency of the signal.

A set of 48 measurements were taken with the HRA using a 10 mS, 6000 Hz linear stepped FM waveform in the Gould Island test area against an air-filled steel sphere target located at approximately \( r = 110 \) m, \( \theta = 5^\circ \) and \( \psi = 0^\circ \). The data were processed as follows to estimate the value of \( \theta \). A set of vertical staves were formed from the unweighted element level data and phase-shift beamforming was implemented via an FFT to form 128 beam outputs steered in azimuth. The peak beam output from the target was compared to the data immediately before and after the target to determine \( SNR_{\theta} \). The average value over the 48 data sets was 22 dB. The peak beam output of the target return also provides a coarse estimate of \( \theta \). A refined estimate is derived by least squares fitting a parabola to the peak and three values on either side of the peak. The mean and standard deviation of the refined angle estimates were calculated to be 5.12° and 0.14° respectively. Figure 16 shows a comparison of the standard deviation of the estimates with the bound derived in (3). The in-water result matches fairly well with the theoretical result.
Figure 15: Geometry

Figure 16: Comparison of theoretical angle estimate bound and in-water result

References


