Classification of Underwater Objects Using Synthetic Aperture Sonar Images and Waveforms\textsuperscript{1}

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July 7, 2008

\textsuperscript{1}Partially supported by ONR grant N00014–07-1-0166.  
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Outline

1 Objectives

2 Synthetic Aperture Sonar (SAS)

3 Overall Strategy

4 Experimental Data Measured in a Pond

5 Classification Strategy

6 Future Plan, etc.
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Objectives

- Detection of shallowly-buried objects using wideband FM sonar
- Classification of objects into mines or non-mines
- Characterization of types of mines

(a) Manta

(b) Pdm1
Concept

- Synthetic Aperture Sonar (SAS) for wide range survey
- Buried Object Scanning Sonar (BOSS) for the detailed check

Notional Concept: Synchronous UUV Search and Confirmation
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SAS Operation

Legend
- Point Scatterer
- Sensor
- Reflected Signal

Real Aperture Footprint (Beam pattern)
Along Track
Ping Locations
y,u

Mapped Swath (Range)
Received Signal (Time)
SAS Imagery . . .
This slide demonstrates SSAM’s ability to image small objects with fine detail. Note the scales at right.
A Tough Example

Difficult

CJTFEX off North Carolina - June '04
VSW Ops Area at Courthouse Bay
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Our Overall Strategy

- Two important problems: Detection and Classification
- We tackle the classification problem first.
- We cast the detection problem later as a clustering problem.
- In both cases, shape information alone obtained from reconstructed images from sonar is often ambiguous even after improving image resolution using sophisticated interpolation algorithms.
- Hence, we examine the part of the recorded raw waveforms scattered from the objects that are responsible to form the imaged object of interest.
- We will examine whether we can distinguish material content inside of suspicious objects from waveforms \( \Rightarrow \) acoustic impedance of material.
- We first examine the experimental data obtained in a pond at Naval Surface Warfare Center (NSWC), Panama City, FL.
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Experiment Setup

(a) Pond
Experiment Setup

(a) Pond

(b) Zoom up
Experiment Setup

(a) Rail system

(b) Sonar tower
Experiment Setup . . .

- Source: 10 kHz – 50 kHz sinusoids; 0.2 msec duration
- Fast-time sampling rate: 500 kHz, i.e., $\Delta t = 2 \mu$sec $\implies \Delta x = 0.15$ cm
- Along-track sampling distance, $\Delta u = 2.54$ cm
- Sonar height above bottom = 3.8862 m
- Grazing angle = 20 degree
- Sound velocity in the pond water = 1503 m/s
- Ping rate: about 6–10 pings/sec
- Average 32 pings at each position
We have three different sets of experiments:

- **Experiment 1: Buried**
  - Target: a solid aluminum cylinder (diameter: 30.5 cm; length: 1.52 m)
  - Target location: $x = 10.3$ m (or $t = 14.8$ msec), $y = 4.0 - 5.5$ m; buried about 10 cm below the rippled interface
  - A steel sphere (filled with air) of diameter 25.4 cm was placed in front of the target.

- **Experiment 2: Proud**
  - Target: a solid aluminum cylinder (diameter: 30.5 cm; length: 1.52 m)
  - Target location: the same as above
  - A sphere (filled with silicone oil) of diameter 35.6 cm was placed in front of the target.

- **Experiment 3: Proud Short**
  - Target: a shorter solid aluminum cylinder (diameter: 30.5 cm; length: 60 cm)
  - Target location: the same as above
  - A sphere (filled with silicone oil) of diameter 35.6 cm was placed in front of the target.
Data: 30 kHz Source

(a) Data

(b) Zoom up
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Our Classification Strategy

Step 0: Reconstruct reflectivity images/scenes from SAS data

Step 1: Select objects of interest (at this point manually using a pointing device)

Step 2: Extract raw waveforms corresponding to the selected objects and align/straighten them

Step 3: Apply Local Discriminant Basis (LDB) algorithm to the waveforms

Step 4: Supply top $k$ LDB coordinates to a classifier of one’s choice (e.g., linear discriminant analysis, decision tree, support vector machine, …)

Step 5: Validate the classification rule using test datasets
An Example in a Pond; Step 0: Reconstruct an Image

(a) Buried Cylinder (C1)

(b) Proud Cylinder (C2)
An Example in a Pond; Step 1: Select objects
An Example in a Pond; Step 2: Extract data
Step 2 details: Extraction/Alignment Algorithm

- Indicate the four points of rectangle. (Rectangle shown in green. Point shown in black.)

- Calculate dispersion of four points using dispersion relation

\[
\left(\frac{ct}{2}\right)^2 = x_0^2 + (y - y_0)^2
\]

- \(y\) - cross-range location of the transmitter/receiver
- \(t\) - two-way travel time of the signal
- \((x_0, y_0)\) - location point source
- \(c\) - speed of sound through water

- Use the union of the dispersed points corresponding to all the points in the rectangle to form envelope (indicated in cyan).
Step 2 details: Extraction/Alignment Algorithm . . .

- Assume the object to be extracted consists of a collection of horizontal lines (e.g., a magenta rectangle);
- Construct a rectangular envelope for each horizontal line segment (green points);
- Extract waveform samples contained in envelope and within half of signals wavelength of envelope (red points);
- Using the dispersion relation, map extracted points to their location if dispersed from the center line (black points);
- Interpolate these mapped points to find the values of waveforms at the desired time locations (the same as the center line time samples);
- Repeat this procedure for all the horizontal line segments in the object.
An Example in a Pond; Step 2: Extract data . . .

(a) Cylinder Waveforms

(b) Sphere Waveforms
Step 3: Apply Local Discriminant Basis (LDB) Algorithm

- Developed by Saito and Coifman (1993–5) for extracting localized discriminant features from data using various basis dictionaries (e.g., wavelet packets, local cosines, etc.)
- Selects a complete basis from a specified dictionary by optimizing some discriminant measure of the basis coordinates
- Top few coordinates in terms of the discriminant measure are then fed to any classifier of one’s choice (Linear Discriminant Analysis, Decision Trees, Support Vector Machine, . . . )
- LDB and its variants have been applied to: geophysical signal/image classification; noise reduction in hearing aids; diagnostics of mammography; radar target discrimination; neural spike detection and sorting; face detection, etc.
- Searching the keyword “local discriminant basis” in google.scholar.com immediately shows its impact
Examples of Basis Dictionaries

Standard Basis

Haar Basis

Walsh Basis

C12 Wavelet Packet Basis

Local Sine Basis

Discrete Sine Basis
An Example in a Pond; Step 3: LDB

Figure: (a) Average $C_1$ waveform; (b) Average $S_1$ waveform; (c) The LDB vector #1 trained on $(C_1, S_1)$; (d) The LDB vector #2 trained on $(C_1, S_1)$; (e) The LDB vector #3 trained on $(C_1, S_1)$. 
An Example in a Pond; Step 3: Top 3 LDB coordinates

Figure: Extracted waveforms projected onto the top 3 LDB coordinates. Each point represents a single waveform. The LDB was computed on the \((C_1, S_1)\) dataset.
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Future Plan

- Examine the robustness of the extracted LDB features
- Investigate a new and robust discriminant measure based on Earth Mover’s Distance (EMD), which is related to optimal transport (or the Monge-Kantorovich) problem
- Modify LDB to accept complex-valued signal or phase information
The following articles are available at http://www.math.ucdavis.edu/~saito/publications/


Thank you very much for your attention!
Acknowledgment

- Dan Cook (formerly NSWC-PC)
- Gerry Dobeck (NSWC-PC)
- Carrie Dowdy (formerly NSWC-PC)
- Richard Holtzapple (NSWC-PC)
- Joe Lopes (NSWC-PC)
- ONR
- NSF