IMPROVED TIME-FREQUENCY DE-NOISING OF ACOUSTIC SIGNALS FOR UNDERWATER DETECTION SYSTEM

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To my beloved family, friends and
all those who have contributed in this project

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ABSTRACT

The capability to communicate and perform target localization efficiently in underwater environment is important in many applications. Sound waves are more suitable for underwater communication and target localization because attenuation in water is high for electromagnetic waves. Sound waves are subjected to underwater acoustic noise (UWAN), which is either man-made or natural. Optimum signal detection in UWAN can be achieved with the knowledge of noise statistics. The assumption of Additive White Gaussian noise (AWGN) allows the use of linear correlation (LC) detector. However, the non-Gaussian nature of UWAN results in the poor performance of such detector. This research presents an empirical model of the characteristics of UWAN in shallow waters. Data was measured in Tanjung Balau, Johor, Malaysia on 5 November 2013 and the analysis results showed that the UWAN has a non-Gaussian distribution with characteristics similar to 1/f noise. A complete detection system based on the noise models consisting of a broadband hydrophone, time-frequency distribution, de-noising method, and detection is proposed. In this research, S-transform and wavelet transform were used to generate the time-frequency representation before soft thresholding with modified universal threshold estimation was applied. A Gaussian noise injection detector (GNID) was used to overcome the problem of non-Gaussianity of the UWAN, and its performance was compared with other nonlinear detectors, such as locally optimal (LO) detector, sign correlation (SC) detector, and more conventionally matched filter (MF) detector. This system was evaluated on two types of signals, namely fixed-frequency and linear frequency modulated signals. For de-noising purposes, the S-transform outperformed the wavelet transform in terms of signal-to-noise ratio and root-mean-square error at 4 dB and 3 dB, respectively. The performance of the detectors was evaluated based on the energy-to-noise ratio (ENR) to achieve detection probability of 90% and a false alarm probability of 0.01. Thus, the ENR of the GNID using S-transform denoising, LO detector, SC detector, and MF detector were 8.89 dB, 10.66 dB, 12.7dB, and 12.5 dB, respectively, for the time-varying signal. Among the four detectors, the proposed GNID achieved the best performance, whereas the LC detector showed the weakest performance in the presence of UWAN.

ABSTRAK

Keupayaan untuk berkomunikasi dan melaksanakan sasaran penyetempatan yang cekap bawah air adalah penting dalam banyak aplikasi. Gelombang bunyi adalah lebih sesuai untuk komunikasi dan sasaran penyempatan dalam air kerana pengecilan dalam air adalah tinggi untuk gelombang elektromagnet. Gelombang bunyi adalah tertakluk kepada bunyi akustik bawah air (UWAN), sama ada buatan manusia atau semula jadi. Pengesanan isyarat optimum dalam UWAN boleh dicapai dengan mengetahui tentang statistik hingar. Andaian hingar Gaussian putih tambahan (AWGN) membolehkan penggunaan pengesan korelasi linear (LC). Walau bagaimanapun, sifat bukan-Gaussian untuk UWAN menyebabkan prestasi yang tidak baik terhadap pengesan tersebut. Kajian ini menjelaskan tentang model empirikal bagi ciri-ciri UWAN di perairan cetek. Data diukur di Tanjung Balau, Johor, Malaysia pada 5 November 2013 dan keputusan analisis menunjukkan bahawa UWAN mempunyai pembahagian bukan-Gaussian dengan ciri-ciri yang serupa dengan hingar 1/f. Satu sistem pengesanan lengkap berdasarkan model hingar yang terdiri daripada hidrofon jalur lebar, taburan masa-frekuensi, kaedah nyah-hingar dan pengesanan adalah dicadangkan. Dalam kajian ini pengubahan-S dan pengubahan gelombang digunakan untuk menghasilkan perwakilan masa-frekuensi sebelum pengambangan lembut dengan penganggaran ambang universal terubah digunakan. Pengesan hingar Gaussian (GNID) telah digunakan untuk mengatasi masalah *non-Gaussianity* daripada UWAN, dan prestasinya telah dibandingkan dengan pengesan linear lain, seperti pengesan optimum setempat (LO), pengesan tanda korelasi (SC) dan beberapa lagi pengesan penapis sepadan konvensional (MF). Sistem ini telah dinilai berdasarkan dua jenis isyarat iaitu isyarat termodulasi frekuensi-tetap dan frekuensi linear modular. Untuk tujuan nyah-hingar, pengubahan-S mengatasi pengubahan wavelet dari segi nisbah isyarat-kepada-hingar dan ralat punca min kuasa dua masing-masing pada 4 dB dan 3 dB. Prestasi pengesan dinilai berdasarkan nisbah tenaga-kepada-hingar (ENR) bagi pengesanan kebarangkalian sebanyak 90% dan kebarangkalian penggeraan palsu sebanyak 0.01. Oleh itu, ENR daripada GNID menggunakan nyah-hingar pengubahan-S, pengesan LO, pengesan SC, dan pengesan MF adalah masing-masing 8.89 dB, 10.66 dB, 12.7 dB dan 12.5 dB, untuk isyarat yang berubah dengan masa. Antara empat pengesan, GNID yang dicadangkan mencapai prestasi terbaik manakala pengesan LC menunjukkan prestasi yang paling lemah dengan kehadiran UWAN.

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LIST OF ABBREVIATIONS

AWGGN	-	Additive White Generalized Gaussian Noise
AWGN	-	Additive white Gaussian noise
CC	-	Computation complexity
CWT	-	Continuous wavelet transform
DCT	-	Discrete cosine transform
DFT	-	Discrete Fourier transform
DWT	-	Discrete wavelet transform
ECL	-	Energy congregation level
EMD	-	Empirical mode decomposition
EEMD	-	Ensemble empirical mode decomposition
ENR	-	Energy-to noise ratio
FFT	-	Fast Fourier transform
FIR	-	Finite impulse response
GG	-	Generalized Gaussian
GNID	-	Gaussian noise injection detector
GPR	-	Ground penetrating radar
HIS	-	Hyperspectral image
IIR	-	Infinite impulse response
ISI	-	Intersymbol interference
IWT	-	Inverse wavelet transform
LC	-	Linear correlator
LFM	-	Linear frequency modulated
LMS	-	Least mean square
LO	-	Locally optimal
MF	-	Matched filter

ML	-	Maximum likelihood
MSE	-	Mean square error
NP	-	Neyman-Pearson
NRMSE	-	Normalized root-mean-square error
PD	-	Probability of detection
PEF	-	Prediction error filter
PPT	-	Parts per thousand
PRD	-	Percent root mean square difference
PSD	-	Power spectral density
PSE	-	Power spectral estimation
PWMWF	-	Whitening Multiway Wiener Filter
RMSE	-	Root mean square error
ROC	-	Receiver Operating Characteristic
SC	-	Sign correlation
SNR	-	Signal to noise ratio
SSP	-	Sound speed profile
STFT	-	Short-time Fourier transform
SVD	-	Singular value decomposition
SWPT-SURE	-	Spatial-domain wavelet packet transform with Sure
TD	-	Threshold-system-based detector
UHF	-	Ultrahigh frequency
WSS	-	Wide sense stationary
WT	-	Wavelet transform

LIST OF SYMBOLS

c - sound speed in sea water

T - temperature

d - depth

S - Salinity

$PL_{spreading}$ - Geometric spreading loss

S_f - Spreading factor

R - Transmission range

$PL_{absorbtion}$ - Absorption loss

f - Signal frequency

P - Hydrostatic pressure

f_T - Relaxation frequency

$\alpha(f)$ - Absorption coefficient

PL - Total path loss

$L_A(R)$ - Natural value total path losses

T_s - Symbol duration

T_m - Time delay spread

D_{00} - Distance along direct ray

D_{sb} - Distance covered by the first ray reflected on the surface

D_{bs} - Distance covered by the first ray reflected on the seabed

$L_A(D_{00})$ - Path losses along direct path

$L_A(D_{sb})$ - Path losses covered by the first ray reflected on the surface

$L_A(D_{bs})$ - Path losses covered by the first ray reflected on the seabed

L_{SR} - Surface reflection coefficients

L_{BR} - Sea bottom reflection coefficients

τ_{sb} - propagation delay along the ray length D_{sb}

τ_{bs} - propagation delay along the ray length D_{bs}

$h(\tau, t)$ - channel impulse response

$A_p(t)$ - time-varying path amplitude

$\tau_p(t)$ - time-varying path delay

d_1 - depth of the source

d_2 - depth of the receiver

h - height of the water column

v_m - wind speed

θ - incident angle

σ - rms roughness of the surface

λ_a - acoustic wave length

ρ - density in sea water

ρ_1 - density in the seabed

c_1 - sound speed in the seabed

θ_{sb} - angle of incident corresponding to the ray D_{sb}

θ_{bs} - angle of incident corresponding to the ray D_{bs}

$N_t(f)$ - Turbulence noise

$N_s(f)$ - Shipping noise

$N_w(f)$ - Wind noise

$N_{th}(f)$ - thermal noise

s - shipping density parameter

$S_{xx}(f)$ - overall noise spectrum level

$s(n)$ - Discrete time signal

N - signal duration in samples

A - signal amplitude

$\phi(n)$ - instantaneous phase

T_s - sampling period

α - frequency law

f_{BW} - bandwidth of the signal

$R_{vv}\ (m)$ - Autocorrelation function

$s_{vv}\left[e^{j2\pi f}\right]$ - power spectrum

σ_v^2	-	Variance of noise
σ_v	-	standard deviation of noise
p	-	length of the forward predictor filter
$a_p(n)$	-	filter coefficient
$e_p(n)$	-	forward prediction error
$H_p(z)$	-	transfer function of the PEF
$h_w(n)$	-	impulse response of the whitening filter
$h_{IWF}(n)$	-	impulse response of the inverse whitening filter
$X(t,a)$	-	continuous wavelet transform
a	-	Scale factor
$X(n,k)$	-	discrete wavelet transform
L	-	Number of levels
Δf	-	frequency resolution
$\Delta\tau$	-	Time resolution
$X_D(n,k)$	-	detail coefficients at scale k
$X_A(n,k)$	-	approximate coefficients at scale k
$h_{HP,k}(n)$	-	high-pass filter at scale k
$h_{LP,k}(n)$	-	low-pass filter at scale k
$X(t,f)$	-	S-transform
$g(t,f)$	-	frequency depended Gaussian window
$X(n,k)$	-	Discrete time of S-transform
γ_k	-	modified universal threshold estimation
ξ	-	modified universal threshold factor
$\sigma_{v,k}$	-	k-th noise standard deviation
$X_{D,\gamma}(n,k)$	-	threshold values of the detail coefficients
v_I	-	in-phase component
v_Q	-	quadrature component
$W(k)$	-	scalable localizing Gaussian window
CC_{ST}	-	Computation complexity of S-transform
N_τ	-	lag window length
N_h	-	length of the low-pass and high-pass filters
CC_{DWT}	-	Computation complexity of wavelet transform

P_D	-	detection probability
C_{ij}	-	cost
$l(x)$	-	likelihood ratio
H_0	-	null hypothesis
H_1	-	alternate hypothesis
$\mathrm{P_{FA}}$	-	probability of false alarm
$P(D_i\|H_i)$	-	conditional probability
$\mathrm{P_M}$	-	probability of missing
d	-	degree of freedom
μ_v	-	mean value
$T(x)$	-	test statistic
E_s	-	energy of the signal
$g(x[n])$	-	non-linear transfer function of LO detector
$\Psi(.)$	-	Kummer’s hypergeometric function.
$\Gamma(\cdot)$	-	gamma function
$r_{xx}(t)$	-	autocorrelation function
$P_{welch}\left(e^{jw}\right)$	-	Welch method

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Chapter 1

INTRODUCTION

1.1 Background of Research

Increased interest in defense applications, off-shore oil industry, and other commercial operations provides a motivation for research in signal processing for the underwater environment. In the underwater environment, acoustics waves are more practical for applications such as navigation, communication, and other wireless applications due to the high attenuation rate of electromagnetic waves. Acoustic propagation is characterized by three major factors: attenuation that increases with signal frequency, time-varying multipath propagation, and low speed of sound (1500 m/s) (Stojanovic and Preisig, 2009). No two deployment regions within the ocean with have the same depths ranging from tens of meters to a few kilometers with node placement that varies from one network to another (King *et al.*, 2008). As the attenuation of sound in the ocean is a frequency-dependent process, underwater systems operate at low frequencies, for example, on the order of tens of kHz (Stojanovic and Preisig, 2009). Underwater data communication links generally support low data rates mainly due to the constraints of the communication channel (Burrowes and Khan, 2011; Stojanovic and Preisig, 2009). The main constraints are the high propagation delay, lower effective signal-to-noise ratio (SNR) and lower bandwidth. Sources of underwater acoustic noise (UWAN) are manmade (shipping, aircraft over the sea and machinery sounds on the ship) and natural (rain, wind, marine lifeforms and seismic) (Melodia *et al.*, 2013).

As the attenuation of sound in the ocean is frequency dependent, the ocean acts as a low-pass filter for ambient noise. Results ambient noise power spectral density (PSD) is thus described as colored that is the noise has more power at the lower frequencies and less power at the higher frequencies (Chitre *et al.*, 2004). The ambient noise comes from sources such as turbulence, breaking waves, rain, and distant shipping. While ambient noise is often approximated as Gaussian, in practice it is colored exhibiting a decaying power spectral density (PSD). The rate of decay is at approximately 18 dB/decade (Burrowes and Khan, 2011). The underwater environment consists also site-specific noise (Burrowes and Khan, 2011). Site-specific noise, for example, exists for ice cracking in the polar region and acoustic noise due snapping shrimp in warmer waters. Unlike ambient noise, site-specific noise often contains significant non- Gaussian components.

In many signal processing applications, it is assumed that the noise samples are uncorrelated and typically described as independently identically distributed (i.i.d). Therefore, it is often necessary to transform a vector of observations with correlated noise samples to one in which they are uncorrelated (Therrien, 1992). This thesis is concerned with the de-noising and detection of signals that are generally transmitted by vessels sailing on the surface of the sea that could be due to the acoustic emission of the ship’s engine or machinery and echo locating devices. The goal is to investigate on the techniques for optimal detection of acoustic signals in UWAN. To better understand the underwater operating environment, a comprehensive study was conducted with measurements of UWAN at Tanjung Balau, Johor, Malaysia.

In this thesis, a complete detection system based on the noise models is developed that consists of the broadband hydrophone, pre-whitening filter, time-frequency distribution, de-noising method, inverse whitening filter, and detection. It is proposed to improve the probability of detection (P_D) and increased the energy to noise ratio (ENR) using S-transform based time–frequency de-noising algorithm. The S-transform is used in the de-noising process to improve performance over de-noising using wavelet transform (Al-Aboosi *et al.*, 2016). The performance results using simulated and measured UWAN of the proposed detector Gaussian noise injection detector (GNID) are compared with other nonlinear detectors, namely, a locally optimal (LO) detector, a sign correlation (SC) detector, and a conventional LC detector.

1.2 Problem Statement

UWAN affects signal detection and parameters estimation. This is true in the reliability of signal detection where the noise is non-white and non-Gaussian. The sound attenuation in the sea is frequency dependent and this causes the sea acts as a low-pass filter for UWAN. The resulting PSD of UWAN is best described as colored where the noise has more power at the lower frequencies compared to the higher frequencies. Therefore, the noise samples are uncorrelated and the assumption of i.i.d is no longer valid resulting in poor detection performance.

The UWAN is often approximated as colored where the observed signal samples follows Gaussian probability density function (pdf). In practice, the signal observed on certain sites has significant non-Gaussian components. For example, ice cracking in the polar region and snapping shrimp in warmer waters. As a result, the detection methods that assume Gaussian pdf do not achieve optimum performance in UWAN. The effect of non-Gaussian pdf and colored noise further degrades the performance of the detection system such as underwater data communication and target locating. Further detector improvement performance can be achieved by combining non-linear detectors and de-noising process with pre-whitening techniques.

Signal de-noising is important if it is of interest to recover information in a signal that is corrupted by noise. For noise that is modeled as additive white Gaussian noise (AWGN), the frequency components of noise are evenly distributed over all frequency range while the signal of interest lies within a specific range in frequency. De-noising using time-frequency based method can be used to recover the signal from noise. Universal threshold estimation method is used widely to calculate the threshold value. Most critical is to find the suitable threshold value to ensure that the signal is recovered from noise. If the threshold value is too high, part of the original signal could be removed while a value too low could result in the insertion of noise in the signal.

1.3 Objectives

1. To characterize UWAN for shallow water in Malaysian seas based on statistical properties such as power spectral estimation (PSE), autocorrelation function and probability density function (PDF).

2. To de-noise the acoustic signal in UWAN using the time-frequency representation generated by the S-transform with soft thresholding using the modified universal threshold estimation. The comparison is made with the conventionally used wavelet transform de-noising method.

3. To adopt methodologies used to de-noise a known signal in presence of colored noise that include pre-whitening filter, signal transformation and single-level and level-dependent thresholding method.

4. To design detection methods using linear and non-linear detectors for optimal or near-optimal performance in UWAN.

1.4 Scope of Work

This research focuses mainly on the de-noising and detection of acoustic signals using time-frequency representation. The scopes of this project are as follows:

1. The measurements were done in shallow water at Tanjung Balau, Johor, Malaysia with a maximum sea depth of 10 meters. The first set of measurements was done at different depths while another set was done to observe the diurnal difference in UWAN characteristics.

2. Samples of UWAN collected using a broadband hydrophone (7 Hz ~ 22 kHz) DolphinEAR 100 Series model with a maximum cable length 10 meters.

3. The Nyquist rate is used to convert the measured signal in continuous time to discrete time. Since the underwater acoustic signals is in the 0-2500 Hz frequency band, the sampling frequency is fs=2W which the minimum requirement for digital sonar system. By making the sampling frequency greater than 2W, the sampling frequency selected is 8000 Hz.

4. Different modulation signals are generated in MATLAB can be transmitted underwater using BII-8030 underwater acoustic transmitter for frequency range (20Hz to 100 kHz).

5. The UWAN can be assumed stationary because the variability of the predominant sources (wind speed and shipping density) and propagation variation (such as temperature and density) changes more slowly compare to the signal duration of interest.

6. Comparing the distributions obtained from the collected data with Gaussian distribution done by using distribution fitting tool in MATLAB to knowledge the pdf of the UWAN.

7. The signals used are divided into two types, namely, single-frequency sinusoidal signal and linear frequency modulated (LFM) signal, which respectively represent fixed-frequency signals and time-varying signals normally encountered in practical situations.

1.5 Research Procedure

The research procedure is as follows:

1. **Literature review:** Reviews on underwater communications, underwater acoustic noise models, time-frequency representation, signal de-noising, and signal detection.

2. **Data Collection:** Collect samples of noise from different depth in Malaysian seas using Hydrophone Dolphin EAR 100 Series (two field trials).

3. **Data Analysis:** Analyze noise samples and characterized them using Welch power spectrum estimation technique, the autocorrelation function of noise and probability density function (PDF). Also, to investigate the diurnal variability of UWAN characteristics.

4. **Pre-whitening filter:** Since the UWAN is colored noise, pre-whitening of the signal performs before the de-noising operation is implemented using the same methods use for white noise.

5. **De-noising technique:** The S-transform and the wavelet transform are used to generate the time-frequency representation before soft thresholding with universal threshold estimation is applied to de-noise the acoustic signals.

6. **Detection Theory:** Detection of the acoustic signal in the presence of UWAN, Gaussian noise injection detector (GNID) is proposed to overcome the problem of non-Gaussianity of the UWAN, and its performance compared with matched filter (MF) detector and other non-linear detectors. The performance of the detectors is evaluated based on the energy-to-noise ratio (ENR) and receiver operating characteristic (ROC) curves.

7. **Simulation validation:** To validate the performance of the complete detection system proposed. The complete detection system based on the noise models consist of the broadband hydrophone, pre-whitening filter, time-frequency distribution, de-noising method, inverse whitening filter, and detection.

8. **Discussion and result.**

1.6 Contributions of Work

1. In this work, a signal de-noising and detection system for acoustic signals corrupted by underwater acoustic noise (UWAN) is proposed. The proposed system overcomes the limitation caused by the characteristics of UWAN in shallow waters, which is identified as a key performance hurdle for communication systems.

2. The proposed Gaussian noise injection detector (GNID) detector based on noise-enhanced signal detection using an S-transform de-noising

method aims to ensure that the noise follows a Gaussian distribution, improve the detection probability (P_D), and increase the energy-to-noise ratio (ENR) in comparison with other nonlinear detectors exclusively used for non-Gaussian detection. Thus far, this method has not been presented in previous research for sonar and underwater communication applications.

3. The S-transform de-noising method based on time–frequency analysis is proposed as an alternative to the wavelet transform. From the time–frequency representation generated by the S-transform, de-noising is performed using soft thresholding with modified universal threshold estimation. The threshold value for a single level estimation method is determined in the case of using a pre-whitening filter or the multilevel estimation method. Afterward, soft thresholding is applied to suppress the noisy coefficients and reconstruct the signal using the inverse S-transform. Thus far, no work based on S-transform de-noising used this methodology, and most of the previous works assumed that the noise is white and applied a mask window to the time–frequency domain representation of noisy signal to remove noises.

1.7 Thesis Organization

This thesis is organized as follows: Chapter 2 discusses a brief review of related topics, such as the sound speed profile, underwater propagation effects, underwater transmission loss, underwater channel model, non-Gaussian signal detection methods, UWAN characteristics and model, signal whitening and de-noising, and signal detection. Chapter 3 provides the details of the proposed signal de-noising technique using S-transform and the proposed detection systems in presence of UWAN. Chapter 4 presents the experimental and simulation results. Chapter 5 presents the conclusion and recommendations for future research.

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