ADAPTIVE TIME-FREQUENCY DISTRIBUTION FOR ACCURATE REPRESENTATION OF RADAR SIGNALS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

AUGUST 2017

Specially dedicated to my lovely parents, my family, friends and all those who have contributed in this research.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere appreciation to mysupervisor, Assoc. Prof. Dr. Ahmad Zuri Bin Sha'ameri for his continuous guidance, suggestions, comments and encouragement in the journey of making this research project a success. Without his thoughtful views and ideas this thesis would not have been as what was presented here.

In addition, my gratitude goes to the Sultan Iskandar Foundation Johor for its financial support and Universiti Teknologi Malaysia for providing the resources for this research. Other than that, I would also like to thank the entire DSP Laboratory and Embedded System Laboratory team members who have contributed through ideas, feedbacks and supports.

Last but not least, my family also deserve special thanks for their endless patience, support and understanding throughout my studies. My sincere gratitude also extends to all my colleagues who have provided their ever ending assistance at various occasions and ways.

ABSTRACT

Electronic Support is one of the key elements in electronic warfare where the main interest is to detect and classify emitted radar signals. Quadratic time-frequency distribution (TFD) is often used to represent this type of signal due to its high resolution representation in time and frequency. However, it is greatly affected by the cross-terms which cause inaccurate signal interpretation. The purpose of this study is to design a cross-term suppression technique for a non-cooperative environment where the exact signal characteristics are unknown. A new adaptive directional ambiguity function Wigner-Ville distribution (ADAF-WVD) is developed to adaptively estimate the kernel parameters based on the ambiguity properties of a signal. Two adaptive procedures, which are the Doppler-lag block searching and the ambiguity domain energy concentration estimation are developed to separate the auto-term from the cross-term in the ambiguity domain. ADAF-WVD measures the energy level of the signal in the ambiguity domain to distinguish between the auto-terms and cross-terms. Four radar signal types are used to verify the accuracy of the time-frequency representation (TFR): simple pulse, Costas coded, pulsed linear frequency modulation and continuous wave linear frequency modulation. Accurate TFRs are produced for most of the signal as low as at signal-to-noise ratio (SNR) of -1 dB. The performance of instantaneous frequency estimation is verified using Monte Carlo simulation. Both approaches are proven to be efficient estimators as they meet the requirements of the Cramer-Rao Lower Bound at SNR > 6 dB. The computational complexity of ADAF-WVD is four times lower than the adaptive smooth window cross Wigner-Ville distribution. Thus, it has been demonstrated that the developed TFD is an efficient solution for the analysis of radar signals.

ABSTRAK

Sokongan Elektronik merupakan elemen penting dalam peperangan elektronik yang mana fungsi utamanya adalah untuk mengesan dan mengelas pancaran isyarat-isyarat radar. Taburan masa-frekuensi (TFD) kuadratik sering digunakan untuk mewakilkan isyarat-isyarat jenis ini disebabkan resolusi perwakilan yang tinggi bagi masa dan frekuensi. Namun ianya sangat terkesan dengan istilah-silang yang menyebabkan ketidaktepatan dalam penafsiran isyarat. Tujuan kajian ini adalah untuk mereka bentuk teknik penindasan istilah-silang bagi persekitaran bukan-kerjasama di mana cirian sebenar isyarat tidak diketahui. *Adaptive directional ambiguity function Wigner-Ville distribution* (ADAF-WVD) yang baharu dibangun bagi menganggar parameter-parameter kernel secara ubah suaian berdasarkan sifat-sifat ketaksaan isyarat. Dua tatacara boleh suai, iaitu carian blok *Doppler-lag* dan anggaran penumpuan tenaga domain ketaksaan dibangun bagi mengasingkan istilah-auto dengan istilah-silang di dalam domain taksa. ADAF-WVD mengukur paras tenaga isyarat dalam domain taksa bagi membezakan istilah-auto dan istilah-silang. Empat jenis isyarat radar digunakan bagi pengesahan ketepatan perwakilan masa-frekuensi (TFR): denyut ringkas, berkod Costas, modulatan dedenyut frekuensi linear, dan modulatan gelombang terus frekuensi linear. TFR yang tepat dapat dihasilkan bagi hampir kesemua isyarat pada nisbah isyarat-hingar (SNR) serendah -1 dB. Prestasi penganggaran frekuensi seketika dinilai menggunakan simulasi Monte Carlo. Kedua-dua pendekatan terbukti sebagai penganggar yang cekap memandangkan mereka mencapai had bawah Cramer-Rao pada SNR > 6 dB. Kekompleksan perkomputeran bagi ADAF-WVD adalah empat kali ganda lebih rendah berbanding *adaptive smooth window cross Wigner-Ville distribution*. Oleh itu, telah terbukti bahawa TFD yang dibangunkan merupakan penyelesaian yang cekap bagi menganalisa isyarat-isyarat radar.

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LIST OF ABBREVIATIONS

ADAF-WVD	-	adaptive directional ambiguity function WVD
AD-ECE	-	Ambiguity domain energy concentration estimation
AF	-	Ambiguity function
AMC	-	Adaptive modulation and coding
AOK	-	Adaptive optimal kernel
ARM	-	Anti-radiation missile
ASW-WVD	-	Adaptive smooth window WVD
AW-WVD	-	Adaptive window WVD
AWGN	-	Additive white Gaussian noise
BMA	-	Block matching algorithm
BW	-	Bandwidth
C2	-	Command and control
CC4	-	Costas coded 4
CEI	-	Constant energy interval
CP	-	Cyclostationary processing
CRLB	-	Cramer-Rao lower bound
CW-LFM	-	Continuous wave LFM
DE	-	Directed energy
DI	-	Doppler-independent
DLBS	-	Doppler-lag block searching
DPT	-	Discrete polynomial-phase transform
EA	-	Electronic attack
EM	-	Electromagnetic
EP	-	Electronic protection
ES	-	Electronic support measure
EW	-	Electronic warfare

EMD - Empirical mode decomposition
HEC - High energy concentration
IDFT - Inverse discrete Fourier transform
IAF - Instantaneous autocorrelation function
IF - Instantaneous frequency
ISR - Intelligence, surveillance and reconnaissance
LE - Lag marginal
LFM - Linear frequency modulation
LI - Lag-independent
LPI - Low probability intercept
MBD - Modified B-distribution
MSE - Mean square error
NCW - Network-centric warfare
PLFM - Pulse LFM
PRP - Pulse repetition period
PSK - Pulse shift keying
PW - Pulse width
QMFB - Quadrature mirror filter bank
QTFD - Quadratic TFD
TFA - Time-frequency analysis
TFD - Time-frequency distribution
TFR - Time-frequency representation
RADAR - Radio detection and ranging
RGK - Radial Gaussian kernel
SAD - Sum of absolute difference
SDR - Software defined radio
SNR - Signal-to-noise ratio
SP - Simple pulse
SSR - Secondary surveillance radar
STFT - Short time Fourier transform
WVD - Wigner-Ville distribution
ZAM - Zhao-Atlas-Marks
ZC - Zero-crossing

LIST OF SYMBOLS

f	-	Signal frequency
f_s	-	Sampling frequency
f_{dev}	-	Frequency deviation
FT	-	Fourier transform
$z(t)$	-	Analytical form of the signal
$w_a(\tau)$	-	Analysis window width in lag
τ	-	Time delay
v	-	Frequency delay
$\rho(t,f)$	-	Quadratic time-frequency distribution
$K_z(t,\tau)$	-	Bilinear product or time-lag function
$A(v,\tau)$	-	Ambiguity domain or Doppler-lag function
$g(t,\tau)$	-	Separable kernel
T_p	-	Period for a pulse
T_b	-	Period for a sub-pulse
Δf	-	Frequency bandwidth
τ_g	-	Lag window width
v_G	-	Doppler window width
$A_{z,thd}$	-	Ambiguity function threshold value
$A(0,0)$	-	Highest energy point at the ambiguity domain
$\underset{t}{*}$	-	Convolution in time
$\underset{f}{*}$	-	Convolution in frequency

CHAPTER 1

INTRODUCTION

1.1 Background

Radio detection and ranging or RADAR is an important sensor for target detection and tracking. Radar in military perspective is usually used in tracking enemy missiles, ships, aircraft, and satellites. Effective radar system should be able to provide information about the position of enemy targets which later be used in threat recognition and evaluation. Radar is also used extensively in civilian field applications such as air traffic control, ocean surveillance, terrestrial traffic control and weather sensing [1].

Electronic Warfare (EW) constitutes the manipulation electromagnetic (EM) environment with the intention of providing an advantage over the adversary in the utilization of EM spectrum. Electronic support (ES) which is one of the three major divisions in EW is responsible for collecting and analyzing all the radiated EM to fulfill the spectrum operations for a given command [2]. ES also covers the application of spectrum monitoring to ensure that the EM environment can be used by civilian without impeding the military access.

Due to high peak power, conventional radar signals can be easily detected and located by modern intercept receiver. Low probability intercept (LPI) radar is introduced that utilized special emitted waveform to avoid detection and interception [3]. Thus, intercepting LPI signals is not easy but not totally impossible. Modern intercept receivers with channelized receiver, utilization of superheterodyne receiver and sidelobe detection capability are among important properties that are required for intercepting LPI signals [4], [5].

Signal processing algorithms are the important components of modern intercept receiver that improves the detection and analysis of LPI radar. Examples of methods used for detecting and analyzing LPI radar are adaptive match filtering, parallel filter arrays with higher order statistics, Wigner-Ville distribution (WVD), quadrature mirror filter bank (QMFB), and cyclostationary processing (CP) [5].

1.2 Problem Statement

In radar, the presence of the noise leads to false detection, false alarm, and inaccurate signal parameters estimation. Some of the factors are noise background which usually assumed as white Gaussian noise, microwave line noise, receiver noise, and receives antenna ohmic loss noise. Errors in receiving signal can be classified as external or internal errors. Internal errors come from the radar system itself such as system noise temperature but are not covered in this work. The external error means the errors originated not from the system but from the outside sources such as deliberate electronic interference (jammers), backscatter and multipath [6]. In addition, meteorological phenomena such as rain, snow, and cloud can cause the attenuation of the signal especially for the signal that transmits above X-band [7].

A non-stationary signal such as LPI radar signal whose spectral description depend on time is best analysed with time-frequency distribution (TFD). Among TFD classes, quadratic TFD (QTFD) is widely used because it provides high resolution representation both in time and frequency [8]. Cross-terms are introduced in QTFD due to the quadratic nature of the algorithm which cause problem to interpret the true signal characteristics and it also exaggerates the effect of noise [9]. Kernel function is introduced in QTFD as a solution to suppress cross-terms and obtaining an accurate TFR.

Most of the time, ES applications dealing with a non-cooperative environment situation where the prior knowledge of the true signal characteristics – pulse repetition period (PRP), frequency agilities, modulation techniques, pulse width (PW), and pulse amplitude - are unknown. Signal dependent TFD requires a TFD that is able to preserve the maximum concentration of the signal component to its proper support in the TF domain for a broad class of signal types – radar and communication [10]. The main challenge is the cross-terms characteristics differs from one signal to another. Signal dependent kernel solves this problem but the kernel parameters has to be estimated first. Kernel parameters estimated manually provided the signal characteristics are known. However, the kernel parameters have to be estimated adaptively in a non-cooperative environment. Some of the adaptive kernel TFDs such adaptive optimal kernel smooth-windowed Wigner-Ville distribution (AOK-SWVD) [11] and adaptive smoothed windowed cross Wigner-Ville distribution (ASW-WVD) [12] are limited to communication signals such as amplitude shift keying (ASK) and frequency shift keying (FSK) signal. While, the adaptive optimal kernel TFD (AOK-TFD) [13] is only suitable for linear frequency modulation (LFM) signal. The time-frequency reassignment and synchrosqueezing [14] although applicable for many types of signals requires a significantly high computational complexity. Therefore, there is a need for an adaptive QTFD that is suitable for broader class of signals in a non-cooperative environment.

The time-frequency (TF) methods can be class into linear, bilinear (quadratic) and high-order species. Linear TF methods such as spectrogram have no cross-terms issue and comparatively low in computational complexity but suffer from low-resolution signal representation. The high order TF distribution can achieve higher concentration and special features. However, high order TF has relatively complicated computation [15]. Typically for QTFD, it will require more than N^2 log2 N operations and N^2 sample points of memory where N is the length of the signal [16]. Such intensive computational complexity and large memory requirement make the implementation for near real-time application are not possible.

1.3 Objectives

The objectives of this research are:

1. To model the characteristics of various types of radar signals in ambiguity domain.
2. To design adaptive procedure (adaptive ambiguity energy concentration estimation and Doppler-lag block searching) to estimate the kernel parameters (Doppler and lag window) for accurate TFD in a non-cooperative environment.
3. To implement computationally efficient separable kernel QTFD suitable to represent radar signals.

1.4 Project Scope

The scopes of this research are:

1. The quadratic time-frequency distribution (QTFD) based on the Wigner-Ville distribution (WVD) is used in this research.
2. Existing SDR equipment and antenna at the DSP Lab UTM is used to receive signals to verify the time-frequency distribution.
3. A sampling of the signal is set at the Nyquist rate. The sampling frequency is 40MHz and maximum frequency is 20MHz.
4. Signals used in this research are a simple pulse signal, Costas coded signal, linear FM signal (LFM), and continuous wave linear FM signal (CW-LFM). According to [3] all the modulation techniques mention above can be used to generate secure LPI waveforms.
5. During the development, testing and benchmarking of the algorithm, MATLAB software will be used as the simulation tools.
6. The estimated IF variance from the peak of time-frequency representation (TFR) is benchmarked with the CRLB for IF estimate.
7. The developed technique is tested with captured signal at Senai International Airport and UTM Observatory for actual signal application performance.
8. The multipath fading environment is not considered in this study.

1.5 Contribution of Work

This research proposed an adaptive kernel QTFD for the estimation of signal parameters. These new techniques are able to cover a broader class of radar signals compared to the previous work [17]–[20] that only capable of catering for a limited class of signals. Adaptive optimal kernel TFD (AOK-TFD) as an example is very good in representing linear FM signal, especially in low SNR. However, this approach failed to resolve the signal characteristics from the cross-terms when it comes to nonlinear FM signal such as Costas coded signal. Although , the reassignment is method suitable for many TFD, it introduces a lot of additional computational cost [18].

The new adaptive directional ambiguity function Wigner-Ville distribution (ADAF-WVD) developed with optimized computational complexity and improved accuracy IF estimation. Computational load for the developed kernel is reduced by taking into account the symmetric property of the signal in the ambiguity plane. This work successfully improves the existing kernel specific QTFD algorithm in terms of computational load and memory utilization. Realizations of miniature QTFD processor for mobility and performance advantages in future are possible by the implementation of separable kernel TFD that greatly reduce the computational complexity and utilization of memory.

ADAF-WVD designed specifically to work in a non-cooperative environment where the prior knowledge of incoming signal is not required in the analysis. The adaptive kernel incorporated in the proposed methods enable the kernel to adjust its size depending on the signal of interest for the sole purpose of providing the optimal TFD against a wide range of LPI signal classes.

1.6 Thesis Organization

The thesis is divided into five chapters starting with Chapter 1 as introduction. Chapter 2 is the literature review that discusses the basic regarding radar technology, concept of LPI radar, and works that are related to the research. Chapter 3 is focusing on the methodology of implementing fast and efficient separable kernel QTFD. In Chapter 4, the analysis methods are verified using variety of LPI radar signals. The performance of the proposed methods against the actual radar signal also presented here. Conclusion and recommendations for future work are presented in Chapter 6.

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