UNIVERSITI PUTRA MALAYSIA

OPTIMIZED DIFFERENTIAL EVOLUTION ALGORITHM FOR A LINEAR FREQUENCY MODULATION RADAR SIGNAL DENOISING

MOHANAD DAWOOD HASAN AL-DABBAGH

OPTIMIZED DIFFERENTIAL EVOLUTION ALGORITHM FOR A LINEAR FREQUENCY MODULATION RADAR SIGNAL DENOISING

By

MOHANAD DAWOOD HASAN AL-DABBAGH

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

April 2013

DEDICATION

قال تعالى:

((يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِير))

المجادلة 11

This thesis is dedicated to:

My beloved Parents,

My Brother and Sister,

And all my friends,

For

Their Endless Patience and Support

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

OPTIMIZED DIFFERENTIAL EVOLUTION ALGORITHM FOR A LINEAR FREQUENCY MODULATION RADAR SIGNAL DENOISING

By

MOHANAD DAWOOD HASAN

April 2013

Chairman: Assoc. Prof. Raja Syamsul Azmir b. Raja Abdullah, PhD

Faculty: Engineering

In radar systems, the problem of recovering the targets reflections has been a major concern for system designers for decades. One of the first steps for better signal recovery was done by initializing a stable radar signal with high repetition sequence of generated pulses. Stabilizing the radar signal and achieving a better recovery for the received signal, over the years, took a big part of extensive studies on pulse generators and led to the era of analog systems replacement with digital ones. Using the microelectronic circuitries have shown reliability prove in terms of signal generation stability. Chirp pulses are one of the most popular radar signals that can be easily generated using digital technology. In this thesis, Memory Based, and Direct Digital Synthesizer (DDS) architectures as the two most popular chirp signal generation techniques have been designed, by using Altera StratixIII FPGA by the use of Altera QuartusII software. The received signal recording was performed by using MATLAB Software code, connected to the FPGA for getting the received

reflections from the HSMC FPGA daughter board that worked as an Analog-to-Digital and Digital-to-Analog converter. Both architectures gave precise results for different selections of chirp rate that could fit with system specifications.

The main contention of this thesis is to investigate the development of new optimization technique based on Differential Evolution algorithm (DE), applied for radar signal denoising application. The choose of the Differential Evolution was mainly made because, of its simplicity, and reliability scheme that can provide especially, in the applications that require continuous spaces measurements, which was fit to our problem. An improvement to the conventional DE algorithm has been made to change it from its classical form to be possibly applied for ambiguous targets range detection for radar system. The standard DE algorithm is known as a fixed length optimizer, while our problem demands the need for methods that aren't tolerated to a fixed individual size, and that was made by altering the mutation and crossover strategies as well as the selection operation. We propose an optimized crossover scheme that changes the crossover operation from being fixed-length to random-length, which has been designed to fit for the proposed variable length DE. We refer to the new DE algorithm as random variable length crossover DE (rvlx-DE) algorithm.

The measurement results show high capability for target recognition in terms of frequency response and peak forming that has been clearly recognized from noise and clutter distortion, and that was shown more clearly when it was compared with Wavelet Transform and Hilbert-Huang Transform denoising techniques.

Abstrak tesis ini dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

ALGORITMA EVOLUSI PEMBEZAAN TEROPTIMUM UNTUK PEMBUANGAN HINGAR ISYARAT RADAR MODULASI FREKUENSI LINEAR

Oleh

MOHANAD DAWOOD HASAN

April 2013

Pengerusi: Raja Syamsul Azmir b. Raja Abdullah, PhD

Fakulti: Kejuruteraan

Dalam sistem radar, permasalahan untuk mendapatkan isyarat pantulan objek sasaran telah menjadi kebimbangan utama bagi pereka sistem selama beberapa dekad. Salah satu langkah pertama untuk pemulihan isyarat yang lebih baik adalah dengan menghasilkan isyarat radar stabil permulaan dituruti pengulangan berkala isyarat menunjukkan. Kajian yang meluas dalam bidang penstabilan isyarat radar untuk memulihkan isyarat asal telah dilaksanakan serta membawa kepada era penggantian sistem analog kepada digital. Penggunaan litar mikroelektronik dalam penjanaan isyarat telah menghasilkan isyarat yang stabil. Isyarat berdecit adalah diantara isyarat radar yang popular serta mudah dihasilkan dengan menggunakan teknologi digital. Perisian Altera Quartus II telah digunakan untuk mengprogram

Altera Stratix III FPGA dengan menggunakan dua teknik popular penghasilan isyarat berdecit iaitu Berdasarkan Memori dan Pensintesis Terus Digital (DDS). Isyarat yang diterima daripada litar HSMC FPGA yang disambung kepada litar FPGA akan direkodkan dengan menggunakan kod Perisian Matlab. Litar HSMC FPGA ini berfungsi sebagai penukar isyarat analog-kepada-digital dan digital-ke-analog. Kedua-dua teknik ini memberikan hasil yang tepat dalam penghasilan pelbagai isyarat berdecit untuk spesifikasi yang diperlukan.

Penekanan utama tesis ini adalah untuk menyiasat pembangunan teknik pengoptimuman baru dengan menggunakan algoritma Evolusi Berbeza (DE) dalam aplikasi pembuangan hingar isyarat radar. Pemilihan Evolusi Berbeza dibuat kerana, ianya skim yang tidak kompleks serta kestabilan dalam aplikasi yang memerlukan pengukuran ruang yang berterusan selaras dengan masalah semasa. Satu penambahbaikan telah dibuat terhadap algoritma Evolusi Berbeza(DE) yang asal bagi membolehkan ianya diaplikasikan dalam sistem radar untuk tujuan pengesanan kesamaran jarak objek sasaran. Algoritma Evolusi Berbeza(DE) yang asal berfungsi dengan menggunakan pengoptima kepanjangan yang tetap; walaubagimanapun, masalah kami memerlukan teknik yang tidak bertoleransi terdapat saiz individu yang tetap dan ini dilakukan dengan mengubah mutasi serta strategi penyeberangan termasuk operasi pemilihan. Kami mencadangkan skim optimum penyeberangan yang mengubah operasi penyeberangan daripada kepanjangan yang tetap kepada kepanjangan yang rambang yang telah direkabentuk khas untuk cadangan kepanjangan bolehubah DE. Algoritma baru ini dikenali sebagai Algoritma Penyeberangan Pembolehubah Kepanjangan Rawak (rvlx-DE).

Hasil ujikaji yang dilakukan, teknik ini dapat mengenalpasti objek sasaran dengan baik dalam respon frekuensi serta pembentukan puncak yang menunjukkkan ianya dengan mudah dapat dikenalpasti berbanding isyarat hingar serta isyarat persekitaran. Teknik pengasingan isyarat hingar ini lebih jelas apabila dibandingkan dengan teknik Wavelet Transform serta Hilbert-Huang Transform.

ACKNOWLEDGEMENTS

To my Lord Allah Almighty, I am thankful for the blessings and virtues, and for reconcile, strength, patience, courage, and determination he gave me to complete this work to the fullest, Alhamdulillah. This work would not be accomplished without the help of so many people. In the following lines is a brief account of some but not all who deserve my thanks.

I would like to extend my gratitude to Associate Professor Dr. Raja Symsul Azmir b. Raja Abdullah, for his supervision, advice, and guidance from the very early stage of this research as well as giving me extraordinary experiences throughout the work. Above all and the most needed, he provided me unflinching encouragement and support in various ways.

I am also delighted to convey my appreciations to Dr. Fazirulhisyam b. Hashim, for his valuable comments and suggestions which have been indispensable in the preparation of this thesis.

My warmest gratitude goes to all of my family members, especially my father, my mother who always believed in me, gave me all the possible support, and being patient with me for years, providing me with everything, just to make me focus on my goals. I would like to thank my sister for her endless support in so many aspects, by giving me advice and guidance throughout my research and, of course, sharing my happiness and sorrow by being my wonderful home mate for the last few years. I am also thankful for my brother for his support and concern about my study, and his willing to provide me with any support I needed.

I must extend my sincere thanks to the Ministry of Higher Education in Iraq for their support by sponsoring me for three semesters of my study. None the less, my gratitude to the Malaysian people in general for their perfect hospitability in their green land during my study period.

I am deeply thankful for every wonderful friend I met in this country; I am thankful for every word of information, advice, and support. I am grateful for every moment of laugh and sadness we shared together. I am so grateful to have such helpful friends around who always showed concern in my work, and I hope they will accept my apology for not mentioning their names to not forget anyone of them.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Raja Syamsul Azmir b. Raja
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Fazirulhisyam b. Hashim, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institutions.

MOHANAD DAWOOD HASAN AL-DABBAGH

Date: 2 April 2013

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
AWG	Arbitrary Waveform Generators
CMA-ES	Covariance Matrix Adaptation Evolution Strategy
DEGL	DE with Global and Local neighborhoods
DE	Differential Evolution
DSP	Digital Signal Processing
DAC	Digital-to-Analog Converter
DDS	Direct Digital Synthesizer
DFT	Discrete Fourier Transform
DWT	Discrete Wavelet Transform
DTWT	Dual-Tree Wavelet Transform
EMD	Empirical Mode Decomposition
ES	Evolution Strategies
EA	Evolutionary Algorithms
EP	Evolutionary Programming
FFT	Fast Fourier Transform

FPGA	Field Programmable Gate Arrays
FIR	Finite Impulse Response
FT	Fourier Transform
GDE3	Generalized Differential Evolution
GA	Genetic Algorithm
GP	Genetic Programming
HHT	Hilbert-Huang Transform
HSMC	High Speed Mezzanine Connector
IMF	Intrinsic Mode Functions
LFM	Linear Frequency Modulation
LUT	Look-Up Table
LNA	Low Noise Amplifier
LPF	Low Pass Filter
MP	Matching Pursuit
NCO	Numerically Controlled Oscillator
NP	Population Size
OLRR	Open Loop Ring Resonator

ODE	Opposition-Based DE
OE	Optimal Estimate
PSO	Particle Swarm Intelligence
PLL	Phase-Lock Loop
PRI	Pulse Repetition Interval
RA	Radar Altimeter
RCS	Radar Cross Section
Rvlx-DE	Random Variable Length Crossover DE
RTL	Register Transfer Level
SaDE	Self-adaptive Differential Evolution Algorithm
SNR	Signal-To-Noise Ratio
SS	Spectral Subtraction
STFT	Short Time FT
SAR	Synthetic Aperture Radar
TBP	Time Bandwidth Product
VDE	Variable-Length Differential Evolution
VCO	Voltage Controlled Oscillator

WT	Wavelet Transform

LIST OF SYMBOLS

K_0	The VCO Transfer Function
ΔF_{out}	Frequency Shift For The Output Signal
φ	Scaling Function
ψ	Mother Wavelet
K	Chirp Rate
B	Bandwidth
T	Pulse Width
f_{clk}	Clock Frequency
FS	Sampling Frequency
f_o	Output Frequency
φ_{inc}	Binary Phase Increment (Tuning Word)
M	The Phase Accumulator Length
φ_{PM}	Phase Modulation Parameter
t_0	Time Delay
R	Target Range

σ	Noise Level
NP	Population Size
$x_{i,G}$	Target Individual
CR	Crossover Parameter
G	Generation Population
P_G	Initial Population
SD_i	The Individual's Variable Dimension
N	Number Of Parameters
A	RCS For The Target
F	Target Frequency
P	Phase Shift
Y	Vertical Change
$u_{i,G=t}$	Trial Vector
$S_{act}(i)$	Actual Data Received From Targets
$S_{exp}(i)$	Received Data Estimated
δ_r	Range Resolution

CHAPTER 1

INTRODUCTION

1.1 Background

In signal analysis, noise can be defined as an unwanted random addition data that holds no meaning to the received signal; since this data has not been used to transmit the signal, but randomly produced at the receiving stage. High noise levels can be an interference source that may change and distort the received signal. The dominant parameter to measure the signal quality is known as the Signal-to-Noise ratio that calculates the relation between the useful to the irrelevant information in an exchange.

In various fields, related with communications and electronics, scientists are dealing with problems of signal recovery, and noise elimination to extract the bases for the original signal. In radar systems, one of the solutions to get better recovery of the received signal and to get more accurate repetition for the transmitted pulses was done by using digital technology. The signal generation in digital form is becoming a major method of communications in the modern age; different methods have been applied for this purpose, where digital circuitry has proven a reliable stability compared with the analog ones. Signal recording in analog or digital devices are not immune to the noise, which can be random or white noise with no coherency mainly produced in the form of random electrons, and caused by heat, environment, and stray circuitry loses as they influence the output signal voltage thus creating a detectable noise, no matter how sophisticated and precise the circuit design, there is still an urgency for the received signal to be applied in some signal processing techniques before they can be used in applications.

In different fields, of communications engineering, system and electrical engineering, and applied mathematics, signal processing plays an important role in dealing with signals operations and analysis. Over the years, a large number of signal processing techniques have been proposed to reduce the noise, improve the signal-to-noise ratio by extracting the overlapping peaks, and to decompose the transmitted signals into their components. Many of signal processing techniques are base on tiring mathematical operations that were not sufficient to be used before the invention of computerized instrumentation. Nevertheless, in each different application there should be a decision making to decide the most appropriate technique that gives better denoising results.

Signal denoising is directly related to samples estimation of the received signal either by estimating the equation parameters for the target reflections or the surrounding noise and clutter accompanying the data of interest. Differential Evolution algorithm (DE) is one technique proposed by Storn R and Price K in 1996 [1]. It is a simple, efficient, and fast evolutionary algorithm compared with other evolutionary algorithms techniques, and it is suitable for global optimization over continues spaces. It has been implemented to resolve different domains of scientific and engineering problems like circuit [2], antenna [3], filter designs [4], intelligent machines [5], and many others; which indeed solved the optimization problem for parameter estimation in a reliable way. It is currently known that the academics from all disciplines have been using Differential Evolution Algorithm for resolving the optimization problems emerging in their related fields. This occurs because DE has obtained increasing attention as a simple and robust optimizer [6-8].

1.2 Problem Statement

Radar system works on the principle of transmitting the signal and receiving the reflections from the targeted objects, this process encountering challenges to be solved to get the most possible benefit from the signal reflections. The information gathered from reflections is greatly valuable to be used in different radar applications. When radar signal reflected back from objects, most of the transmitted power doesn't make it back to the receiver antenna especially in the case when the targeted objects, as in most of the applications, are not perfectly formed in its shape or in its material to get the best reflections.. Weak radar received signals imposes a number of challenges to the design and badly affects the maximum target range for detection. Nevertheless, noise caused by heat, environment, and stray circuitry loses is another challenge that works as an impediment to the received data. That leads to other problems to be dealt with including:

i) Traditional signal processing techniques for general use: Different signal processing and denoising techniques have been applied, over the years, to improve the signal performance in various applications. Some of signal denoising techniques were able to reduce some of the noise from the data of interest but, still having many challenges in data distortion and noise levels that are similar to the frequency of the noisy data i.e. noise in a range different from the target's range can be eliminated easily with traditional denoising and filtering techniques like: low pass, band pass, and high pass filters. Having denoising techniques that can be applied in different applications might be a general solution to the noise problems, even with the thresholds and iterations possibility of selection, they still keep the door open for errors of leaving some parts of the data not being processed correctly.

ii) DE fixed length chromosomes structure and constraints handling: DE like any other types of evolutionary algorithms, is a fixed length chromosome optimizer; so it is unsuitable to apply for problems that demand the attribution of non-fixed length chromosomes applications. On the other hand, using evolutionary algorithms for data estimation is taking place by calculating the fitness function. Taking the fitness function into account will try to find the least value for that function by changing the number of segments. Repeatedly, the fitness value will get lower value each time a new segment is being added. Depending on the fitness as the only decision making is not practical since the estimation function is going to keep trying to fit itself with actual received signal and that may make the noise to be present again at the denoised signal.

1.3 Aim and Objectives

The aim of this thesis is to develop a modified method to estimate the received signal parameters of the transmitted linear frequency modulated (LFM) radar signal to make a noise removal from the valuable data, which leads to better target detection. To achieve this aim, the following objectives are to be accomplished:

i) To enhance the transmitted signal performance by digitally generating a stable Linear Frequency Modulated signal, with high chirp rate.

ii) To develop a modified optimization technique based on Differential Evolution algorithm applied for radar signal denoising.

iii) To conduct a comparison between the modified denoising technique and other denoising techniques:

- Wavelet Transform.
- Hilbert-Huang Transform.

1.4 Thesis Scope

Radar system in its general form can be categorized into stages, and each stage plays an important role to complete the full signal transmission and better information gathering from target reflections. Radar Signal Generation using Linear Frequency

Modulated (LFM) signals was the radar signal type chosen for this study that was digitally generated using the microelectronics techniques in two different ways to get signal stability rather than the traditional analog signal. Radar circuitry for signal transmission and reception is also important, as the circuit components: carrier frequency, and amplification will be the deciding factor for the type of targeted objects needed to be localized and for the case of the LFM signals, radar circuit design is responsible of the pulse compression technique that takes charge for how the received reflection should be analyzed to find the target peaks, representing the targets location. Stretch processing has been chosen for this study for its circuit design simplicity, and the direct proportional frequency offset to the target range. After the signal being received, in many cases the data that is necessary to localize the targets are affected by noise and signal distortion. Evolutionary algorithm as a part of the global optimization methods has been covered in this study by employing one of its prominent optimizers called Deferential Evolution (DE), which has been identified in literature as a simple and efficient method to tackle various optimization applications, and more specifically in radar received signal parameter estimation. The problem complexity of denoising the radar received signal for multiple target localization, immerge the need to modify the standard DE algorithm from its fixed length structure to be variable length structure. Traditional Signal processing techniques, over the years, have been used to solve the noisy signal problems. In this study a comparison has been established between two well-known denoising techniques: Wavelet Transform and Hilbert-Huang Transform to be compared with the proposed variable length Differential Evolution algorithm.

The study module for this thesis is shown in Figure 1.1.

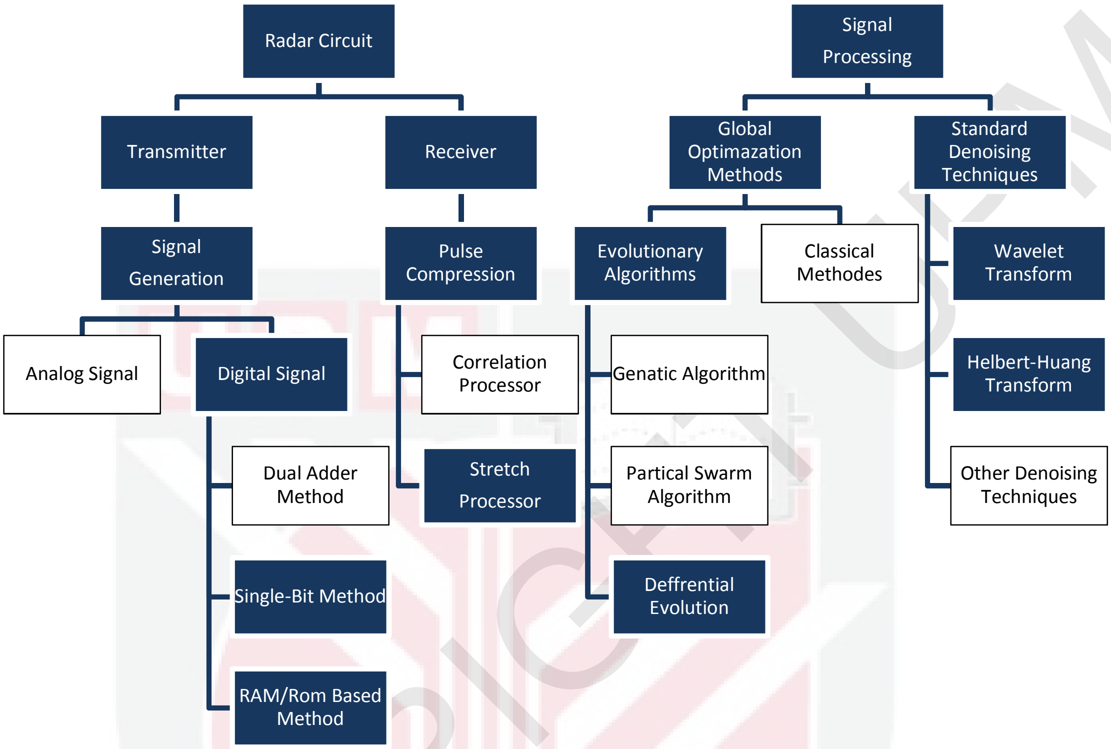

Figure 1-1: Study Module

1.5 Contribution

This thesis is dedicated to find an alternative denoising technique for better targets representation of the transmitted linear frequency modulated radar signal and to get the most possible benefit from the signal reflections. Therefore, in this thesis, the main contributions to attain these objectives are:

i) Equation Modification and Threshold: for the active correlated received signal an equation modification has been made for parameter estimation of targets reflections with lines of thresholds made to act as a constraint, preventing the noise to be present at the estimation function.

ii) An Improved Deferential Evolution Method: The proposed method has mainly altered the mutation and crossover strategies, as well as the selection operation; which has been amended to deal with the complexity of the fitness function and constrains alike. In addition to that, an extended representation scheme for the search variables to determine the length of the individual based on the number of segments included was used. For mutation, two strategies have been proposed, commonly, both strategies are based on choosing the best individual in order to maintain the principle that the best information will be shared among the population. One strategy is applying the standard mutation operation on equal length chromosomes. The second is randomly chosen individuals, then to perform extension or truncation according to the length of the best member among. For both strategies the yield individual will have the same length of the best one. For crossover, a new scheme called rand-length crossover has been designed to fit for the variable length DE. In which the length (i.e. the number of segments) of the new individual will be determined by a random number generated J; the value of J should not exceed the summation length of the mutant parents and the maximum number of expected targets. Ultimately, we refer to the new DE algorithm as random variable length crossover DE (rvlx-DE) algorithm.

1.6 Thesis Organization

The remaining parts of this thesis are organized as follows:

Chapter 2: A review on several arbitrary waveform generators (AWG) have been used to get the digital chirp signal with flexible adjustments to adapt in multiple applications with high signal performance, providing a simplified interface to the user device. Moreover, some of the most popular denoising algorithm is reviewed. Wavelet Transform (WT) and Hilbert-Huang Transform (HHT) are some of the signal denoising techniques that gave high performance in various applications. The ability to estimate the original signal parameters is a dominant factor that releases the signal from its distortion. Finally, the Differential Evolution algorithm as one of the most powerful optimization techniques that have shown a well standing efficacy in different real-world optimization problems in science and engineering has been reviewed with some of its applications.

Chapter 3: The methodology of the design and implementation of chirp signal generator using field programmable gate array (FPGA) using the most popular: memory based, and Direct Digital synthesizer architectures have been discussed with the complete radar system circuitry calculations and match filtering. A discussion on some of the well known signal processing techniques: Wavelet Transform and

Hilbert-Huang Transform have also been made. The standard DE algorithm and the proposed signal denoising algorithm (rvlx-DE) and the specific strategies of the proposed algorithm and its applicability for case study have been discussed. Moreover, the fitness function and its relative constraints are also discussed in details. Finally, the full procedure incorporate the proposed variable DE operations to build up the overall scheme of the rvlx-DE in a pseudo-code fashion were written.

Chapter 4: The experimental results of signal denoising using the standard (DE) and the developed (rvlx-DE) algorithms have been presented and discussed. A comparison in terms of received signal denoising is then established between rvlx-DE, WT, and HHT.

Chapter 5: This chapter summarizes the objectives addressed and presents the conclusions derived from this research. Suggestions for future developments are also been made in this final chapter.

REFERENCES

[1] R. Storn and K. Price, "Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces," *Journal of global optimization,* vol. 11, pp. 341-359, 1997.

[2] S. Yang and A. Qing, "Design Of High Power Millimeter-Wave TM01 – TE11 Mode Converters By The Differential Evolution Algorithm," *Plasma Science, IEEE Transactions on,* vol. 33, pp. 1372-1376, 2005.

[3] S. Goudos, K. Siakavara, T. Samaras, E. Vafiadis, and J. Sahalos, "Self-adaptive differential evolution applied to real-valued antenna and microwave design problems," *Antennas and Propagation, IEEE Transactions on,* pp. 1-1, 2011.

[4] S. K. Goudos and J. N. Sahalos, "Pareto optimal microwave filter design using multiobjective differential evolution," *Antennas and Propagation, IEEE Transactions on,* vol. 58, pp. 132-144, 2010.

[5] B. Subudhi and D. Jena, "Differential evolution computation applied to parameter estimation of induction motor," *Archives of Control Sciences,* 2009.

[6] Y. Jin and J. Branke, "Evolutionary optimization in uncertain environments-a survey," *Evolutionary Computation, IEEE Transactions on,* vol. 9, pp. 303-317, 2005.

[7] S. Das, A. Konar, and U. K. Chakraborty, "Improved differential evolution algorithms for handling noisy optimization problems," in *Evolutionary Computation, 2005. The 2005 IEEE Congress on*, 2005, pp. 1691-1698.

[8] H. G. Beyer and B. Sendhoff, "Evolution strategies for robust optimization," in *Evolutionary Computation, 2006. CEC 2006. IEEE Congress on*, 2006, pp. 1346-1353.

[9] Y. K. Chan and S. Y. Lim, "Synthetic aperture radar (SAR) signal generation," *Progress In Electromagnetics Research,* vol. 1, pp. 269-290, 2008.

[10] R. Durrant and S. Parkes, "The implementation of high time bandwidth chirp pulses using digital techniques," 1991, pp. 8/1-8/6.

[11] Y. Ephraim and D. Malah, "Speech enhancement using a minimum-mean square error short-time spectral amplitude estimator," *Acoustics, Speech and Signal Processing, IEEE Transactions on,* vol. 32, pp. 1109-1121, 1984.

[12] P. Crozier, B. Cheetham, C. Holt, and E. Munday, "Speech enhancement employing spectral subtraction and linear predictive analysis," *Electronics Letters,* vol. 29, pp. 1094-1095, 1993.

[13] D. L. Donoho, "De-noising by soft-thresholding," *Information Theory, IEEE Transactions on,* vol. 41, pp. 613-627, 1995.

[14] G. Devuyst, J. Vesin, P. Despland, and J. Bogousslavsky, "The matching pursuit: a new method of characterizing microembolic signals?," *Ultrasound in medicine & biology,* vol. 26, pp. 1051-1056, 2000.

[15] S. Mallat, *A Wavelet Tour of Signal Processing*: 2nd ed. New York Academic, 1999.

[16] D. L. Donoho and J. M. Johnstone, "Ideal spatial adaptation by wavelet shrinkage," *Biometrika,* vol. 81, pp. 425-455, 1994.

[17] A. Cohen, J. Froment, and J. Istas, "Analyse multirésolution des signaux aléatoires," *Comptes rendus de l'Académie des sciences. Série 1, Mathématique,* vol. 312, pp. 567-570, 1991.
[18] A. Cohen and J. P. D'Ales, "Nonlinear approximation of random functions," *SIAM Journal on Applied Mathematics,* pp. 518-540, 1997.
[19] A. Graps, "An introduction to wavelets," *Computational Science & Engineering, IEEE,* vol. 2, pp. 50-61, 1995.
[20] A. Antoniadis, J. Bigot, and T. Sapatinas, "Wavelet estimators in nonparametric regression: a comparative simulation study," *Journal of Statistical Software,* vol. 6, pp. 1-83, 2001.
[21] C. S. Burrus, R. A. Gopinath, and H. Guo, "Introduction to Wavelets and Wavelet Transforms: A Primer," *Recherche,* vol. 67, p. 02, 1998.
[22] J. Littlewood and R. Paley, "Theorems on Fourier series and power series (II)," *Proceedings of the London Mathematical Society,* vol. 2, p. 52, 1937.
[23] A. P. Calderón, "Intermediate spaces and interpolation, the complex method," 1964.
[24] J. Morlet, G. Arens, E. Fourgeau, and D. Giard, "Wave propagation and sampling theory; Part I, Complex signal and scattering in multilayered media," *Geophysics,* vol. 47, pp. 203-221, 1982.
[25] A. Grossmann and J. Morlet, "Decomposition of Hardy functions into square integrable wavelets of constant shape," 1984.
[26] Y. Meyer, "Orthonormal wavelets," in *Wavelets*, *Time-Frequency Methods and Phase Space* (Lecture Notes on IPTI), J.M. Combes *et al.*, Eds. New York: Springer-Verlag 1989, p. 21.
[27] I. Daubechies, "Where do wavelets come from? A personal point of view," *Proceedings of the IEEE,* vol. 84, pp. 510-513, 1996.
[28] B. B. Hubbard, "The world according to wavelets: the story of a mathematical technique in the making," 1996.
[29] G. Strang, "Wavelets and dilation equations: A brief introduction," *SIAM review,* pp. 614-627, 1989.
[30] O. Rioul and M. Vetterli, "Wavelets and signal processing," *Signal Processing Magazine, IEEE,* vol. 8, pp. 14-38, 1991.
[31] R. Polikar, "The story of wavelets," *Physics and modern topics in mechanical and electrical engineering,* pp. 192-197, 1999.
[32] G. Strang and T. Nguyen, *Wavelets and filter banks*: Cambridge University Press, 1996.
[33] M. Vetterli and J. Kovačević, *Wavelets and subband coding*: Prentice Hall PTR Upper Saddle River, NJ, 1995.
[34] R. M. Rao and A. S. Bopardikar, *Wavelet transforms: Introduction to theory and applications* vol. 20: Addison--Wesley Longman, Inc.}, 1998.
[35] J. S. Walker, *A primer on wavelets and their scientific applications*: CRC press, 1999.
[36] J. C. Goswami and A. K. Chan, *Fundamentals of wavelets: theory, algorithms, and applications* vol. 219: Wiley, 2011.
[37] A. Jensen and A. la Cour-Harbo, *Ripples in mathematics: the discrete wavelet transform*: Springer Verlag, 2001.

[38] G. Kaiser, *A friendly guide to wavelets*. Boston, MA: Birkhauser, Springer, 1994.
[39] L. Debnath, *Wavelet transforms and their applications*: Birkhauser, Boston, 2002.
[40] I. Daubechies, *Ten lectures on wavelets* vol. 61: Society for Industrial Mathematics, 1992.
[41] S. G. Chang, B. Yu, and M. Vetterli, "Adaptive wavelet thresholding for image denoising and compression," *Image Processing, IEEE Transactions on,* vol. 9, pp. 1532-1546, 2000.
[42] N. E. Huang, Z. Shen, S. R. Long, M. C. Wu, H. H. Shih, Q. Zheng, N. C. Yen, C. C. Tung, and H. H. Liu, "The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis," *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,* vol. 454, pp. 903-995, 1998.
[43] Z. Wu and N. E. Huang, "A study of the characteristics of white noise using the empirical mode decomposition method," *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences,* vol. 460, pp. 1597-1611, 2004.
[44] P. Flandrin, G. Rilling, and P. Goncalves, "Empirical mode decomposition as a filter bank," *Signal Processing Letters, IEEE,* vol. 11, pp. 112-114, 2004.
[45] A. Boudraa, J. Cexus, and Z. Saidi, "EMD-based signal noise reduction," *International Journal of Signal Processing,* vol. 1, pp. 33-37, 2004.
[46] R. Storn and K. Price, "Differential evolution-a simple and efficient adaptive scheme for global optimization over continuous spaces," *International computer science institute-publications-TR,* 1995.
[47] P. Thomas and D. Vernon, "Image registration by differential evolution," 1997, pp. 221-225.
[48] R. Storn, "Differential evolution design of an IIR-filter," 1996, pp. 268-273.
[49] R. Storn, "System design by constraint adaptation and differential evolution," *Evolutionary Computation, IEEE Transactions on,* vol. 3, pp. 22-34, 1999.
[50] J. Liu and J. Lampinen, "A fuzzy adaptive differential evolution algorithm," 2002, pp. 606-611 vol. 1.
[51] M. J. A. Strens and A. W. Moore, "Policy search using paired comparisons," *The Journal of Machine Learning Research,* vol. 3, pp. 921-950, 2003.
[52] H. A. Abbass, R. Sarker, and C. Newton, "PDE: A Pareto-frontier differential evolution approach for multi-objective optimization problems," 2001, pp. 971-978 vol. 2.
[53] J. Brest, S. Greiner, B. Boskovic, M. Mernik, and V. Zumer, "Self-adapting control parameters in differential evolution: A comparative study on numerical benchmark problems," *Evolutionary Computation, IEEE Transactions on,* vol. 10, pp. 646-657, 2006.
[54] A. Qin, V. Huang, and P. Suganthan, "Differential evolution algorithm with strategy adaptation for global numerical optimization," *Evolutionary Computation, IEEE Transactions on,* vol. 13, pp. 398-417, 2009.
[55] J. Zhang and A. C. Sanderson, "JADE: adaptive differential evolution with optional external archive," *Evolutionary Computation, IEEE Transactions on,* vol. 13, pp. 945-958, 2009.

[56] L. J. Fogel, A. J. Owens, and M. J. Walsh, "Artificial intelligence through simulated evolution," 1966.
[57] J. H. Holland, *Adaptation in natural and artificial systems*: University of Michigan press, 1975.
[58] I. Rechenberg, "Evolutionsstrategie: Optimierung technischer Systeme nach Prinzipien der biologischen Evolution. frommann-holzbog, Stuttgart, 1973," *Step-Size Adaptation Based on Non-Local Use of Selection Information. In Parallel Problem Solving from Nature (PPSN3),* 1994.
[59] W. Banzhaf, J. Koza, C. Ryan, L. Spector, and C. Jacob, "Genetic programming," *Intelligent Systems and their Applications, IEEE,* vol. 15, pp. 74-84, 2000.
[60] R. Storn and K. Price, "Differential evolution a simple evolution strategy for fast optimization," *Dr. Dobb's Journal,* vol. 22, pp. 18-24, 1997.
[61] R. Storn, "On the usage of differential evolution for function optimization," 1996, pp. 519-523.
[62] S. Das, A. Abraham, U. K. Chakraborty, and A. Konar, "Differential evolution using a neighborhood-based mutation operator," *Evolutionary Computation, IEEE Transactions on,* vol. 13, pp. 526-553, 2009.
[63] S. Rahnamayan, H. R. Tizhoosh, and M. M. A. Salama, "Opposition-based differential evolution," *Evolutionary Computation, IEEE Transactions on,* vol. 12, pp. 64-79, 2008.
[64] N. Hansen and A. Ostermeier, "Completely derandomized self-adaptation in evolution strategies," *Evolutionary computation,* vol. 9, pp. 159-195, 2001.
[65] K. Price, *New Ideas in Optimization*: McGraw-Hill Publishing Company

1999.
[66] J. Vesterstrom and R. Thomsen, "A comparative study of differential evolution, particle swarm optimization, and evolutionary algorithms on numerical benchmark problems," 2004, pp. 1980-1987 Vol. 2.
[67] P. N. Suganthan. Available: http://www3.ntu.edu.sg/home/epnsugan/index_files/cec-benchmarking.htm
[68] C. Blum and A. Roli, "Metaheuristics in combinatorial optimization: Overview and conceptual comparison," *ACM Computing Surveys (CSUR),* vol. 35, pp. 268-308, 2003.
[69] S. Das and P. N. Suganthan, "Differential evolution: A survey of the state-of-the-art," *Evolutionary Computation, IEEE Transactions on,* vol. 15, pp. 4-31, 2011.
[70] V. Plagianakos, D. Tasoulis, and M. Vrahatis, "A review of major application areas of differential evolution," *Advances in differential evolution,* pp. 197-238, 2008.
[71] A. Qing, *Differential evolution: fundamentals and applications in electrical engineering*: Wiley-IEEE Press, 2009.
[72] S. K. Goudos, Z. D. Zaharis, and T. V. Yioultsis, "Application of a differential evolution algorithm with strategy adaptation to the design of multi-band microwave filters for wireless communications," *Progress In Electromagnetics Research,* vol. 109, pp. 123-137, 2010.

[73] N. I. Dib, S. K. Goudos, and H. Muhsen, "Application of Taguchi's optimization method and self-adaptive differential evolution to the synthesis of linear antenna arrays," *Progress In Electromagnetics Research,* vol. 102, pp. 159-180, 2010.
[74] H. Yuan and J. He, "Evolutionary design of operational amplifier using variable-length differential evolution algorithm," 2010, pp. V4-610-V4-614.
[75] R. Andraka and A. Berkun, "FPGAs make a radar signal processor on a chip a reality," 1999, pp. 559-563 vol. 1.
[76] S. Dasgupta, S. Das, A. Biswas, and A. Abraham, "On stability and convergence of the population-dynamics in differential evolution," *Ai Communications,* vol. 22, pp. 1-20, 2009.
[77] A. Salman, A. P. Engelbrecht, and M. G. H. Omran, "Empirical analysis of self-adaptive differential evolution," *European Journal of operational research,* vol. 183, pp. 785-804, 2007.
[78] S. Das, A. Abraham, and A. Konar, "Automatic clustering using an improved differential evolution algorithm," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* vol. 38, pp. 218-237, 2008.
[79] A. Mandal, H. Zafar, S. Das, and A. V. Vasilakos, "A modified differential evolution algorithm for shaped beam linear array antenna design," *Progress In Electromagnetics Research,* vol. 125, pp. 439-457, 2012.
[80] R. Li, L. Xu, X. W. Shi, N. Zhang, and Z. Q. Lv, "Improved differential evolution strategy for antenna array pattern synthesis problems," *Progress In Electromagnetics Research,* vol. 113, pp. 429-441, 2011.
[81] M. Y. Chua and V. C. Koo, "FPGA-based chirp generator for high resolution UAV SAR," *Progress In Electromagnetics Research,* vol. 99, pp. 71-88, 2009.
[82] A. Corporation, "NCO MegaCore Function User Guide," ed, 2011.
[83] I. Skolnik, "Radar Handbook (3rd)," ed: McGraw-Hill Professional, New York, USA, 2008.
[84] Y. K. Chan and V. C. Koo, "An introduction to synthetic aperture radar (SAR)," *Progress In Electromagnetics Research,* vol. 2, pp. 27-60, 2008.
[85] B. R. Mahafza, *Radar signal analysis and processing using MATLAB*. London, U.K.: Chapman & Hall/CRC, 2009, ch. 7 pp. 315-352.
[86] R. S. A. Raja Abdullah, M. F. A. Rasid, and M. K. Mohamed, "Improvement in detection with forward scattering radar," *SCIENCE CHINA Information Sciences,* vol. 54, pp. 2660-2672, 2011.
[87] B. Le, Z. Liu, and T. Gu, "Weak LFM signal dectection based on wavelet transform modulus maxima denoising and other techniques," *International journal of wavelets, multiresolution and information processing,* vol. 8, p. 313, 2010.
[88] S. Weijun and Z. Ying, "Wavelet Transform Threshold Noise Reduction Methods in the Oil Pipeline Leakage Monitoring and Positioning System," 2010, pp. 1091-1094.
[89] S. J. Vaishali, "Literature Review of Wavelet based Digital Image Watermarking Techniques," *International Journal of Computer Applications,* vol. 31, pp. 28-35, 2011.

[90] R. Ganesan, K. TAPAS, and V. Venkataraman, "Wavelet-based multiscale statistical process monitoring: A literature review," *IIE transactions,* vol. 36, pp. 787-806, 2004.
[91] Z. Huang, B. Fang, X. He, and L. Xia, "Image denoising based on the dyadic wavelet transform and improved threshold," *Int. J. Wavelets Multiresolut. Inf. Process,* vol. 7, pp. 269-280, 2009.
[92] S. K. Mitra and Y. Kuo, *Digital signal processing: a computer-based approach* vol. 2: McGraw-Hill New York, 2006.
[93] K. M. Chang and S. H. Liu, "Gaussian noise filtering from ECG by wiener filter and ensemble empirical mode decomposition," *Journal of Signal Processing Systems,* vol. 64, pp. 249-264, 2011.
[94] J. M. Ramirez, J. M. Gonzalez, and T. O. Ruben, "An investigation about the impact of the optimal reactive power dispatch solved by DE," *International Journal of Electrical Power & Energy Systems,* vol. 33, pp. 236-244, 2011.
[95] B. Liu, L. Wang, Y. H. Jin, D. X. Huang, and F. Tang, "Control and synchronization of chaotic systems by differential evolution algorithm," *Chaos, Solitons & Fractals,* vol. 34, pp. 412-419, 2007.
[96] J. Wang and Y. Zhao, "Differential Evolution Algorithm Based One Dimension Real Valued Searching for Feature Selection

Future Intelligent Information Systems." vol. 86, D. Zeng, Ed., ed: Springer Berlin Heidelberg, 2011, pp. 127-134.
[97] Y. Ao and H. Chi, "Experimental study on differential evolution strategies," 2009, pp. 19-24.
[98] J. Lampinen, "Solving problems subject to multiple nonlinear constraints by the differential evolution," 2001, pp. 50-57.
[99] J. Lampinen and I. Zelinka, "On stagnation of the differential evolution algorithm," 2000, pp. 76-83.
[100] U. K. Chakraborty, *Advances in differential evolution* vol. 143: Springer Verlag, 2008.
[101] X. Yao, Y. Liu, and G. Lin, "Evolutionary programming made faster," *Evolutionary Computation, IEEE Transactions on,* vol. 3, pp. 82-102, 1999.
[102] J. Liu and J. Lampinen, "A fuzzy adaptive differential evolution algorithm," *Soft Computing-A Fusion of Foundations, Methodologies and Applications,* vol. 9, pp. 448-462, 2005.