

UNIVERSITY OF TECHNOLOGY SYDNEY  
Faculty of Engineering and Information Technology

**Heartbeat Detection with complicated Noises  
Using FMCW Radar**

by

**Jingwei Liu**

A THESIS SUBMITTED  
IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE

**Master of Research**

Sydney, Australia

2021

## Certificate of Authorship/Originality

I, Jingwei Liu declare that this thesis, is submitted in fulfilment of the requirements for the award of Master of Computer Science, in the FEIT at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

Production Note:  
Signature removed  
Signature: prior to publication.

Date:22/1/2021

# ABSTRACT

## Heartbeat Detection with complicated Noises Using FMCW Radar

by

Jingwei Liu

Remote heartbeat detection is particularly useful for applications in smart home, digital health, and disaster relief (e.g. earthquakes) because of its ability to conduct accurate monitoring of heartbeats at a long distance. The millimeter wave band is of great significance for remote heartbeat detection, and the millimeter wave-based frequency modulated continuous radar (FMCW) radar is an excellent device for remote heartbeat detection. In the research of radar-based heartbeat detection, an important problem is the interference of human motion in the signal. Artifacts caused by motion appear across all frequency bands, thereby polluting the true heartbeat waveforms. Therefore, removing random body motion (RBM)'s interference to heartbeat detection has become the most challenging task at present. In this thesis, the heartbeat detection technology based on FMCW radar is studied and contributions to the research of the following two issues is made:

1. In heartbeat detection, greatly reduce the interference of motion artifacts and background noise when using the sparsity difference to extract the heartbeat waveform.
2. The subject's small degree of random movement (upper body movement, lower body static) caused greater interference.

For the first question, we use convolutional sparse coding (CSC) to replace the sparse coding (SC) in the previous work. In order to simulate complex phase noise and motion artifacts, we use gaussian mixture model (GMM) to model the noise. When solving the CSC problem, in order to speed up the entire process, we use (non-convex inexact accelerated proximal gradient) niAPG to achieve rapid decline. Simulations and experiments verify the effectiveness of our method. For the second question,

we added an additional clustering step to the ordinary decomposition algorithm, and proposed new parameters to improve the accuracy of clustering. We extract the initial static data as the initial input, and compare the data of two adjacent time windows to extract the peak heartbeat. For the task of extracting the heartbeat from the target of the upper body motion (large range of random motion), our method proved effective.

# Dedication

To my parents Yin Xu and Shengxi Liu.

## Acknowledgements

First and foremost, I would like to extend my deepest gratitude to my principal professor Andrew. J. Zhang. His patience and enlightening instruction allowed me to see who a real professor is. Without his teachings, I would not have finished this thesis. I also extend my thanks to Professor Richard Xu. His professionalism and work attitude impressed me deeply. I also thank my parents. Finally, I'd like to thank all my friends, especially Chunrui Liu, Zhengguo Shi, and Andre Pearce. Thank you for your guidance and help.

Jingwei Liu  
Sydney, Australia, 2021.

# List of Publications

## Conference Papers

**Jingwei Liu**, and J.Andrew.Zhang, “Gaussian Mixture Model based Convolutional Sparse Coding for Radar Heartbeat Detection,” *Proc. IEEE Int. Conf. on ICSPCS*, Dec. 14-16, 2020.

# Contents

Certificate	ii
Abstract	iii
Dedication	v
Acknowledgments	vi
List of Publications	vii
List of Figures	x
Abbreviation	xii
Notation	xiii
<b>1 Introduction</b>	<b>1</b>
1.1 Background of Human Activity Recognition . . . . .	1
1.2 Motivation and Objectives . . . . .	3
1.3 Approach and Contribution . . . . .	4
1.4 Organisation of the Thesis . . . . .	4
<b>2 Literature review</b>	<b>6</b>
2.1 CW Radar for Heartbeat Monitoring . . . . .	6
2.2 FMCW Radar for Heartbeat Monitoring . . . . .	13
2.3 RBM and RSM Cancellation . . . . .	16
<b>3 Gaussian Mixture Model Based Convolutional Sparse Coding for Radar Heartbeat Detection</b>	<b>28</b>



3.1	System Model . . . . .	28
3.2	Methods of GMM-CSC . . . . .	30
3.2.1	APG . . . . .	33
3.3	Simulation and Experimental Results . . . . .	37
3.3.1	Simulation . . . . .	38
3.3.2	Experimental Results . . . . .	39
<b>4</b>	<b>Advanced Singular Spectrum Analysis Method for Radar Heartbeat Detection</b>	<b>46</b>
4.1	Cluster Methods . . . . .	46
4.2	Pre-Processing and System Structure . . . . .	50
4.3	Advanced SSA for Heartbeat Extraction . . . . .	52
4.3.1	Signal Decomposition . . . . .	52
4.3.2	Reconstruction and Clustering . . . . .	53
4.3.3	HR Estimation . . . . .	55
4.4	Experiment of ASSA . . . . .	58
<b>5</b>	<b>Conclusion</b>	<b>65</b>
5.1	Conclusion . . . . .	65
5.2	Future work . . . . .	66
	<b>Bibliography</b>	<b>67</b>

## List of Figures

2.1	I/Q output and vital signs detected . . . . .	7
2.2	Simple CW radar block diagram . . . . .	8
2.3	Detection result at null observation point . . . . .	10
2.4	Harmonics in normalized baseband spectrum . . . . .	12
2.5	Predicted and measured spectrum density of baseband phase fluctuation at baseband for different time delays . . . . .	13
2.6	T-A and T-F of chirps . . . . .	14
2.7	Overview of FMCW structure . . . . .	15
2.8	IF signal change according to small distance change . . . . .	16
2.9	Data constellation with or without DC information . . . . .	17
2.10	The result measured at null point compared with wired finger pulse sensor . . . . .	18
2.11	The build of RBM noise elimination method based on the detection of both sides of the human body . . . . .	21
2.12	The build of RBM noise elimination method based on a radar-camera sensing system . . . . .	22
2.13	The build of RBM noise elimination method based on a self- and mutually injection-locked radar architecture . . . . .	23
2.14	The build of RSM noise elimination method based on a bi-static structure . . . . .	27
2.15	The build of RSM noise elimination method based on a RF tag . . . . .	27

2.16	The build of RSM noise elimination method based on a FHDF system	27
3.1	System structure and signal pre-processing.	29
3.2	Constellation correction of the received complex signal	30
3.3	Structure of GCSC	30
3.4	Simulation result	40
3.5	CSC and GMM-CSC results in frequency domain.	41
3.6	Scene setup for experiment.	42
3.7	Unwrapped-phase signal with time period 25 seconds	42
3.8	Change in frequency domain after GMM-CSC	43
3.9	Heartbeat signal extracted.	43
3.10	Two-target experimental set up.	44
3.11	Range-FFT figure.	45
4.1	System structure and signal pre-processing.	51
4.2	Comparison between two components with different S	55
4.3	Scene setup for experiment.	59
4.4	Signal from different groups in experiment	61
4.5	Cluster of components in reconstructed signal	62
4.6	Chosen cluster in Frequency domain	63
4.7	Heartbeat Times(per minute) with different processing methods	64

# Abbreviation

APG - Accelerated Proximal Gradient

BSS - Blind Source Separation

CSC - Convolutional Sparse Coding

ECG - Electrocardiography

EM - Expectation Maximization

EMD - Empirical Mode Decomposition

FMCW - Frequency Modulated Continuous Wave

ICA - Independent Component Analysis

GMM - Gaussian Mixture Model

IF - Intermediate Frequency

LO - Local Oscillator(In some down-convert process, LO signal can be treated as transmitted signal)

MIMO - Multi input multi output

MA - Motion Artifact

PPG - Photoplethysmography

RBM- Random Body Movement

RMSE - Root Means Square error

RSM - Random System Movement

SHSC - Second Harmonic Signal Component

SSA - Singular Spectrum Analysis

## Nomenclature and Notation

Capital letters denote matrices.

Lower-case alphabets denote column vectors.

$(\cdot)^T$  denotes the transpose operation.

$I_n$  is the identity matrix of dimension  $n \times n$ .

$0_n$  is the zero matrix of dimension  $n \times n$ .

$\mathbb{R}$ ,  $\mathbb{R}^+$  denote the field of real numbers, and the set of positive reals, respectively.