University of Technology Sydney (UTS)

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Theories and Applications of Non-Contact Sleep Monitoring using Microwave Doppler Radar

by

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under the principle supervision of

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Certificate of Original Authorship

I, Vinh Phuc Tran declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy (PhD), in the Faculty of Engineering and Information Technology (FEIT), School of Biomedical Engineering at the University of Technology Sydney (UTS).

This thesis is wholly my own work unless otherwise reference 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 scholarship.

Signature: Production Note:
Signature removed prior to publication.

Date: 21 February 2020

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Thesis Structure

The structure of the Thesis is the “Conventional Thesis”, adhering to the “2019 UTS Graduate Research Candidature Management, Thesis Preparation and Submission Procedures”. The structure of Thesis is as follows:

- **Publications** – this is a list of published academic conference and journal papers, as well as journal paper submitted and under peer-review at the time of Thesis submission.

- **Patents** – this is a list of published patents, including world international patent (WIPO), US patent and filed provisional Australian IP (AusPat) applications.

- **Statement of Contribution** – this is a summary section documenting the contributions of the Thesis to the knowledge of the non-contact sleep monitoring field.

- **List of Tables** – this section provides a list of tables in the Thesis.

- **List of Figures** – this section provides a list of figures in the Thesis.

- **Acronyms and Abbreviations** – this section provides a list of acronyms and abbreviations in the Thesis.

- **Abstract** – this is a summary of the research works in the Thesis.

- **Chapter 1: Literature Review (*Thesis Contribution 1 – Knowledge*)** – Chapter 1 provides a comprehensive review of the current state of the non-contact microwave Doppler radar sleep monitoring technology. It also outlines the current challenges and recommendations for future research directions.

- **Chapter 2: Sleep Disorders (*Thesis Contribution 1 – Knowledge*)** – Chapter 2 provides an overview of the sleep disorders and focuses on obstructive sleep apnea (OSA). The purpose of chapter 2 is to outline the basic fundamentals of sleep disorders and to provide the background knowledge for the research work in the Thesis.

- **Chapter 3: Relative Demodulation (*Thesis Contribution 2 – Novel Theory 1*)** – Chapter 3 presents a novel real-time demodulation theory and technique for the non-contact microwave Doppler radar system. Included in this chapter, is a novel respiratory and heart rates estimation algorithm, using the non-contact microwave Doppler radar.

- **Chapter 4: Pulmonary Ventilation Mathematical Model (*Thesis Contribution 3 – Novel Theory 2*)** – Chapter 4 presents a novel pulmonary ventilation mathematical model that defines the relationship between the intrapulmonary pressure and the chest displacement. Included is this chapter, is a novel tidal volume estimation algorithm, using the non-contact microwave Doppler radar.

- **Chapter 5: External Ventilation Mathematical Model (*Thesis Contribution 4 – Novel Theory 3*)** – Chapter 5 presents a novel mathematical model that quantitatively defines the relationships between the arterial oxygen saturation (SaO_2), the arterial partial pressure of oxygen (PaO_2) and the arterial partial pressure of carbon dioxide ($PaCO_2$). Included in this chapter is a novel non-contact algorithm that utilizes the mathematical model, multilayer perceptron (MLP) artificial neural network (ANN) and the non-contact microwave Doppler radar, to translate the human periodic chest displacements caused by respiratory efforts into peripheral capillary oxygen saturation (SpO_2) measurements.

- **Chapter 6: 3-Dimensional Feature Representation and Extraction Technique (*Thesis Contribution 5 – Novel Theory 4*)** – Chapter 6 presents a novel 3-dimensional feature representation and extraction technique, consisting of two methods, Spatial Dimensions Transform (SDT) and Spatial Dimensions Decomposition (SDD). SDT and SDD when combined can achieve data transformation, augmentation, normalization, scaling, and feature extraction in a single process.

- **Chapter 7: Novel Real-life Applications and Results of Non-Contact Sleep Monitoring (*Thesis Contribution 6 – Novel Real-Life Applications and Results*)** – Chapter 7 presents the real-life non-contact sleep monitoring applications of the novel contributions theories and techniques presented in chapters 3, 4, 5 and 6. The applications demonstrate the non-contact monitoring of the following sleep parameters:

    1. Respiratory rate.
    2. Heart rate.
    3. Tidal volume.
    4. Body orientations, i.e., “Prone”, “Upright”, “Supine”, “Right” and “Left” sleep orientations.
    5. Oxygen saturation.

- **Conclusion** – this section includes the “Statement of Conclusion” for the research presented in the Thesis.

- **Appendix I** – this section includes the descriptions of the non-contact microwave Doppler radar biosensor used in the research and presented in the Thesis.

- **Appendix II** – this section includes the descriptions of the patients’ databases, including ethics approval used in the research and presented in the Thesis. Additionally, this section also includes the justifications for the data exclusions, selections and partitions.

- **Appendix III** – this section includes the descriptions of common hyperparameters utilized in the artificial neural networks (ANN) and covered in the Thesis.

- **References** – this section includes a list of references utilized in the Thesis.

Publications

Published Conference Papers

1. V. P. Tran, and A. A. Al-Jumaily, "Non-Contact Dual Pulse Doppler System based Respiratory and Heart Rates Estimation for CHF Patients," in 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, MiCo – Milano Conference Center – Milan, Italy, 2015, pp. 4202-4205.

2. V. P. Tran, and A. A. Al-Jumaily, "Non-Contact Real-Time Estimation of Intrapulmonary Pressure and Tidal Volume for Chronic Heart Failure Patients," in 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Orlando, Florida USA, 2016, pp. 3564-3567.

3. V. P. Tran, and A. A. Al-Jumaily, "Non-Contact Doppler Radar Based Prediction of Nocturnal Body Orientations Using Deep Neural Network for Chronic Heart Failure Patients," in 2017 International Conference on Electrical and Computing Technologies and Applications (ICECTA), American University of Ras Al Khaimah, Ras Al Khaimah, United Arab Emirates (UAE), 2017.

Published Journal Papers

4. V. P. Tran, and A. A. Al-Jumaily, "Non-Contact Dual Pulse Doppler System Based Real-Time Relative Demodulation and Respiratory & Heart Rates Estimations for Chronic Heart Failure Patients," *Procedia Computer Science*, vol. 76, no. 2015, pp. 47–52, 2015.
   (Best paper awarded at IEEE-IRIS conference in 2015)

5. V. P. Tran, A. A. Al-Jumaily, and S. M. S. Islam, "Doppler Radar-Based Non-Contact Health Monitoring for Obstructive Sleep Apnea Diagnosis: A Comprehensive Review," *Big Data and Cognitive Computing*, vol. 3, no. 3, pp. 1-21, 2019.

6. V. P. Tran, and A. A. Al-Jumaily, "A Novel Oxygen-Hemoglobin Model for Non-Contact Sleep Monitoring of Oxygen Saturation," *IEEE Sensors Journal*, vol. 19, no. 24, pp. 12325-12332, 2019.

Submitted Journal Paper

7. V. P. Tran, and A. A. Al-Jumaily, "A Novel 3-Dimensional Feature Representation and Extraction Technique with Non-Contact Sleep Monitoring Applications," *IEEE Sensors Journal, 2020*.

Patents

Published World International Patent (WIPO)

1. (WO2019079855) DETECTION AND MONITORING OF BODY ORIENTATION
   https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2019079855
   Publication date: 02-May-2019

2. (WO2016205891) DIAGNOSIS AND MONITORING OF CARDIO-RESPIRATORY DISORDERS
   https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2016205891
   Publication date: 29-Dec-2016

Published US Patent

3. (US20180153427) DIAGNOSIS AND MONITORING OF CARDIO-RESPIRATORY DISORDERS
   https://patentscope.wipo.int/search/en/detail.jsf?docId=US219626659
   Publication date: 07-Jun-2018

Filed Australian Provisional IP (AusPat) Applications

4. Non-contact monitoring of nocturnal body position
   http://pericles.ipaustralia.gov.au/ols/auspat/applicationDetails.do?applicationNo=2018900724
   Filed date: 06-Mar-2018

5. Non-contact monitoring of nocturnal body position
http://pericles.ipaustralia.gov.au/ols/auspat/applicationDetails.do?applicationNo=2017904337
Filed date: 26-Oct-2017

6. Non-contact monitoring of nocturnal oxygen saturation in the arterial blood
http://pericles.ipaustralia.gov.au/ols/auspat/applicationDetails.do?applicationNo=2016903946
Filed date: 28-Sep-2016

7. Estimation of Pulmonary Ventilation Quantities Based On Non-Contact Sensor Data
http://pericles.ipaustralia.gov.au/ols/auspat/applicationDetails.do?applicationNo=2016900897
Filed date: 10-Mar-2016

8. Heart and respiratory rate estimation from non-contact sensor data
https://pericles.ipaustralia.gov.au/ols/auspat/applicationDetails.do?applicationNo=2015902494
Filed date: 26-Jun-2015

Statement of Contribution

The Thesis is a response to the demands for non-contact sleep monitoring systems. The demands arise due to the limitations of the polysomnography (PSG) system, the importance of early screening for obstructive sleep apnea (OSA), the need for long-term continuous monitoring and the concern with respect to patient discomfort when using the current gold-standard PSG system.

The Thesis presents novel theories, real-life applications and the results of the non-contact sleep monitoring using the microwave Doppler radar, including the "non-stationary" and the "non-direct facing" subjects' measurements in the complex sleep environment.

The Thesis includes six contributions to the knowledge of the non-contact sleep monitoring field. The six contributions in its entirety, are my own work.

1. Contribution 1: Knowledge

Chapter 1: Literature Review – Chapter 1 adds to the knowledge and understanding of non-contact sleep monitoring field by presenting a comprehensive review of the current state of the non-contact Doppler radar sleep monitoring technology. This chapter includes an outline of the current challenges and recommendations on future research directions.

Chapter 2: Sleep Disorders – Chapter 2 adds to the knowledge and understanding of the non-contact sleep monitoring field and the research work by presenting an overview of the sleep disorders with the focus on obstructive sleep apnea (OSA). The overview includes the epidemiology, pathophysiology, comorbidities and cardiovascular comorbidities associated with OSA.

2. *Contribution 2: Novel Theory 1*

Chapter 3: Relative Demodulation – Chapter 3 contributes to the field of non-contact sleep monitoring by introducing "Relative Demodulation", a novel real-time demodulation theory and technique for the non-contact microwave Doppler radar system. The novelty of the "Relative Demodulation" technique is that it pivots from conventional displacements analysis to introduce derivatives analysis. Included in this chapter, is a novel respiratory and heart rates estimation algorithm that utilizes the "Relative Demodulation" technique and the non-contact microwave Doppler radar.

3. *Contribution 3: Novel Theory 2*

Chapter 4: Pulmonary Ventilation Mathematical Model – Chapter 4 contributes to the field of non-contact sleep monitoring by introducing a novel pulmonary ventilation mathematical model that defines the relationship between the intrapulmonary pressure and the chest displacement. The novelty of the mathematical model is that it enables the capability to estimate tidal volume using the non-contact microwave Doppler radar. Included in this chapter, is a novel tidal volume estimation algorithm that utilizes the mathematical model and the non-contact microwave Doppler radar.

4. *Contribution 4: Novel Theory 3*

Chapter 5: External Ventilation Mathematical Model – Chapter 5 contributes to the field of non-contact sleep monitoring by introducing a novel oxygen-hemoglobin dissociation mathematical model that quantitatively defines the relationships between the arterial oxygen saturation (SaO_2), the arterial partial pressure of oxygen (PaO_2) and the arterial partial pressure of carbon dioxide ($PaCO_2$). The novelty of the mathematical model is that it enables the capability to estimate oxygen saturation using non-contact microwave Doppler radar. Included in this chapter, is a novel non-contact algorithm that utilizes the mathematical model, multilayer perceptron (MLP) artificial neural network (ANN) and non-contact microwave Doppler radar to translate the human periodic chest displacements caused by respiratory efforts into peripheral capillary oxygen saturation (SpO_2) measurements.

5. <u>Contribution 5</u>: *Novel Theory 4*

Chapter 6: 3-Dimensional Feature Representation and Extraction Technique – Chapter 6 contributes to the field of non-contact sleep monitoring by introducing a novel 3-dimensional feature representation and extraction technique, consisting of two methods, Spatial Dimensions Transform (SDT) and Spatial Dimensions Decomposition (SDD). The SDT and SDD when combined can achieve data transformation, augmentation, normalization, scaling, and feature extraction in a single process. The novelty of SDT and SDD is that the feature engineering process is not required. The preprocessing of signals, DC-offsets removal, signals filtering, expert domain knowledge, wavelet packet decomposition and/or time-frequency domain analysis are not required in the process of feature extraction. This technique is applicable to both classification and dynamic time-series regression applications.

6. <u>Contribution 6</u>: *Novel Real-Life Applications and Results*

Chapter 7: Novel Real-Life Applications and Results of Non-Contact Sleep Monitoring – Chapter 7 contributes to the field of non-contact sleep monitoring by presenting the real-life non-contact sleep monitoring applications and the results of the contributions presented in chapters 3, 4, 5 and 6. The contributions of chapter 7 include the novel high accuracy non-contact estimations/predictions of the following sleep monitoring parameters:

1. Respiratory rate.
2. Heart rate.
3. Tidal volume.
4. Body orientations, i.e., “Prone”, “Upright”, “Supine”, “Right” and “Left” sleep orientations.
5. Oxygen saturation.

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Acronyms and Abbreviations

AASM	–	American Academy of Sleep Medicine
ADC	–	Analogue-to-Digital Converter
AF	–	Atrial Fibrillation
AHI	–	Apnea Hypopnea Index
AI	–	Apnea Index
ANN	–	Artificial Neural Network
ANS	–	Autonomic Nervous System
BMI	–	Body Mass Index
BP	–	Blood Pressure (sometimes referred to as Arterial Blood Pressure)
CCD	–	Charge-Coupled Device
CHF	–	Congestive Heart Failure
CO_2	–	Carbon Dioxide
CSA	–	Central Sleep Apnea
CSAS	–	Central Sleep Apnea Syndrome
CSR	–	Cheyne-Stokes Respiration
CW	–	Continuous-Wave
DC	–	Direct Current
ECG	–	Electrocardiography
EM	–	Electromagnetic
FFT	–	Fast Fourier Transform
FIR	–	Finite Impulse Response
FM	–	Frequency Modulated
FMCW	–	Frequency-Modulated Continuous-Wave
FT	–	Fourier Transform
FRC	–	Functional Residual Capacity
HBPF	–	Heart Band-Pass Filter
HF	–	High Frequency
HI	–	Hypopnea Index
HR	–	Heart Rate

HRV – Heart Rate Variability
ICSD – International Classification of Sleep Disorders
ICU – Intensive Care Unit
IP – Intellectual Property
LDV – Laser Doppler Vibrometry
LF – Low Frequency
MHz – Mega Hertz
MLP – Multilayer Perceptron
MTI – Moving Target Indicator
OSA – Obstructive Sleep Apnea
OSAS – Obstructive Sleep Apnea Syndrome
$PaCO_2$ – Arterial Partial Pressure of Carbon Dioxide
PaO_2 – Arterial Partial Pressure of Oxygen
PCO_2 – Partial Pressure of Carbon Dioxide
PSG – Polysomnography
PW – Pulsed-Wave
Radar – Radio Detection and Ranging
RBPF – Respiratory Band-Pass Filter
Rf – Respiration Frequency
RIP – Respiratory Inductive Plethysmography
SaO_2 – Arterial Oxygen Saturation
SD – Sleep Disorders
SDB – Sleep Disordered Breathing
SpO_2 – Peripheral Capillary Oxygen Saturation
SSG – Seismosomnography
STFT – Short Time Fourier Transform
TLC – Total Lung Capacity
UHF – Ultra-High Frequency
UWB – Ultra-Wave Band
Vf – Ventilation Frequency
WPD – Wavelet Packet Decomposition

ABSTRACT

Obstructive sleep apnea (OSA) is a common and potentially lethal sleep disorder affecting at least 4% of adult males and 2% of adult females worldwide. Early detection, treatment and continuous monitoring of OSA are extremely important as it may reduce the risks associated with cardiovascular comorbidities. Polysomnography (PSG) is the gold-standard to diagnose OSA, however there are limitations, such as its unsuitability for long-term continuous monitoring.

The Thesis is a response to the demands for the non-contact sleep monitoring systems. The demands arise due to the limitations of the PSG system, the importance of early screening for OSA, the need for long-term continuous monitoring and the concern with respect to patient discomfort when using the gold-standard PSG system. The research presented in the Thesis are the novel theories, real-life applications and the results of the non-contact sleep monitoring using the non-contact microwave Doppler radar, including the "non-stationary" and "non-direct facing" subjects' measurements in the complex sleep environment.

The novel theories that the Thesis contributes to the field of non-contact sleep monitoring are:

1. Relative Demodulation – a novel theory and technique for real-time demodulation of the subject's chest or abdomen periodic motions using non-contact microwave Doppler radar.

2. Pulmonary Ventilation Mathematical Model – a novel mathematical model of the physiological pulmonary ventilation that enables the estimation of tidal volume using non-contact microwave Doppler radar.

3. External Ventilation Mathematical Model – a novel mathematical model of the physiological external ventilation that enables the estimation of oxygen

saturation using non-contact microwave Doppler radar.

4. 3-Dimensional Feature Representation and Extraction – a novel theory and technique that represents and extracts features in 3-dimensional space. This technique, when combine with the artificial neural networks (ANN) will enable the predictions of body orientations and oxygen saturation using non-contact microwave Doppler radar.

The novel non-contact sleep monitoring real-life applications and results that the Thesis contributes to the field of non-contact sleep monitoring are:

1. Respiratory rate – achieves 91.53% accuracy with median error of ±1.30 breaths/min.

2. Heart rate – achieves 91.28% accuracy with median error of ±6.20 beats/min.

3. Tidal volume – achieves 83.13% accuracy with median error of 57.32 milliliters.

4. Body orientations – achieve high correct classification rate of 99.9%. The misclassification is at a negligible rate of 0.1%.

5. Oxygen saturation – achieves correlation coefficient of 0.92 and the 95% limits of agreement is ±2.7 (% oxygen saturation).

The contributions of the novel theories, real-life applications and the results presented in the Thesis demonstrated a good level of accuracies. The potential applications include non-contact sleep early screening and/or continuous monitoring of the respiratory and heart rates, tidal volume, body orientations and saturation oxygen during sleep. This can be use in homes, hospitals, primary care sectors, nursing home facilities and/or sleep laboratories.