Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
Real-Time Fusion of Wireless Sensor Network Data for Wellness Determination of the Elderly in a Smart Home

A thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Computer Science and Engineering at Massey University, Manawatu, New Zealand

NAGENDER KUMAR SURYADEVARA

2014
Abstract

In this research, I have explored a methodology for the development of efficient electronic real time data processing system to recognize the behaviour of an elderly person. The ability to determine the wellness of an elderly person living alone in their own home using a robust, flexible and data driven artificially intelligent system has been investigated. A framework integrating temporal and spatial contextual information for determining the wellness of an elderly person has been modelled. A novel behaviour detection process based on the observed sensor data in performing essential daily activities has been designed and developed. The model can update the behaviour knowledge base and simultaneously execute the tasks to explore the intricacies of the generated behaviour pattern. An initial decline or change in regular daily activities can suggest changes to the health and functional abilities of the elderly person.

The developed system is used to forecast the behaviour and quantitative wellness of the elderly by monitoring the daily usages of household appliances using smart sensors. Wellness determination models are tested at various elderly houses, and the experimental results related to the identification of daily activities and wellness determinations are encouraging. The wellness models are updated based on the time series analysis formulations. The integrated smart sensing system is capable of detecting human emotion and behaviour recognition based on the daily functional abilities simultaneously. The electronic data processing system can incorporate the Internet of Things framework for sensing different devices, understand and act according to the requirement of smart home environment.
Dedication

I dedicate this thesis to the elderly people living alone.
Acknowledgements

Firstly, I would like to express my sincere gratitude to my Guru: Prof. Subhas Chandra Mukhopadhyay, who has given me the opportunity to undergo my Ph.D. study under his excellent supervision. Prof. Subhas has taught me how to handle complex situations by inducing constructive concepts with fruitful cooperation and providing facilities in a timely manner. I also thank Dr. Ruili Wang and Dr. Ramesh Rayudu who have been my co-supervisors for providing me with valuable suggestions at different stages of my research.

I would particularly like to thank the elderly people (names and addresses are not mentioned due to privacy issues) for their immediate acceptance in deploying the developed home monitoring system at their houses and being tolerant to frequent visits/consultations during the troubleshooting phases of various tasks of the project.

I would like to also thank all my previous and present research scholars working in the School of Engineering and Advanced Technology, Massey University for their kindness and friendship. Many thanks also go to SEAT staff for being supportive in hard times. Financial support from Massey University Doctoral Scholarship program and the School of Engineering and Advanced Technology is also gratefully acknowledged.

I am extremely grateful to my parents, for their sacrifice and giving me the opportunity that they never had. I would also like to express my gratitude to my wife and children for their support in undertaking and sharing the family responsibilities in my absence.
Table of Contents

ABSTRACT .......................................................................................................................... III
DEDICATION ....................................................................................................................... IV
ACKNOWLEDGEMENTS ..................................................................................................... V
TABLE OF CONTENTS ..................................................................................................... VI
LIST OF PUBLICATIONS, CONTRIBUTIONS AND ACHIEVEMENTS DURING THE PHD STUDY (2011-2014) ........................................................................................................ X
LIST OF FIGURES .......................................................................................................... XVIII
LIST OF TABLES ........................................................................................................ XLI
GLOSSARY ................................................................................................................ XXII

CHAPTER 1. INTRODUCTION ....................................................................................... 1

1.1 Background ............................................................................................................. 3
1.2 Problem Statement ............................................................................................... 4
1.3 Need for Determining Wellness of an Elderly Person ....................................... 5
1.4 Scope of the Research ......................................................................................... 5
1.5 Research Direction ........................................................................................... 7
1.6 Novel Contribution of the Research ................................................................. 7
1.7 Research Significance ....................................................................................... 8
1.8 Outline of the Thesis ...................................................................................... 9

CHAPTER 2. LITERATURE REVIEW ............................................................................. 11

2.1 Introduction ......................................................................................................... 11
2.2 Elderly People and Independent Living ........................................................... 12
2.3 Smart Home Systems ......................................................................................... 15
2.4 Components of the Smart Home Systems ....................................................... 15
    2.4.1 Physical Components ........................................................................... 17
    2.4.2 Communication Mechanism ............................................................... 17
    2.4.3 Information Processing ....................................................................... 18
2.5 Comparisons of Smart Home Systems .......................................................... 19
2.6 Review of Methodologies on ADL Recognition in SHMS ....................... 25
2.7 Smart Homes Technologies Users .............................................................. 31
2.8 Advantages of a Smart Home Technology ............................................... 31
2.9 Current Limitations of Smart Home Technologies ..................................... 31
2.10 Chapter Summary .................................................................................... 33

CHAPTER 3. DEPLOYMENT OF WSN IN A HOME ENVIRONMENT AND REAL-
TIME DATA FUSION ..................................................................................... 35

3.1 Introduction ............................................................................................... 35
3.2 Description of the Wireless Sensing Systems .......................................... 36
3.3 Wireless Sensing Systems for Household Objects Monitoring and Control 38
  3.3.1 Type #1 Electrical Household Objects Monitoring and Control Sensing
       System ........................................................................................................ 38
  3.3.2 Type #2 Non-Electrical Objects Sensing System ............................... 42
  3.3.3 Type #3 Contact Sensing System for Domestic Objects ................. 43
  3.3.4 Type #4 PIR Sensing System for Movements Monitoring ............... 43
  3.3.5 Type #5 Environmental Parameters Monitoring Sensing System ...... 44
  3.3.6 Type #6 Physiological Parameters Monitoring System ....................... 46
3.4 Networking Wireless Sensing Systems ..................................................... 46
  3.4.1 Advantages of XBee Modules ................................................................. 47
3.5 Topologies of Wireless Sensing System ................................................. 47
3.6 Placement of Different Sensing Systems in a Home................................. 49
3.7 Required Number of Sensing Systems at an Elderly Person Home .......... 50
3.8 Real-Time Heterogeneous Sensor Data Fusion ........................................ 52
3.9 Software System for Sensor Data Acquisition ........................................ 54
3.10 WSN Data Storage Mechanism ............................................................... 54
3.11 Query Processing Mechanism for the WSN Data Stream ....................... 56
3.12 Results ..................................................................................................... 59
  3.12.1 Sampling rates for Wireless Sensing Systems .................................. 60
  3.12.2 Quality of Service factors of the Wireless Sensing Systems ......... 62
3.12.3 Reliability ................................................................. 65
3.12.4 Throughput Measurements ....................................... 66
3.12.5 Database Statistics ................................................... 69

3.13 Troubleshooting with XBee Modules .............................. 76
3.14 Limitations of the Wireless Sensing Systems .................. 77
3.15 Chapter Summary .......................................................... 78

CHAPTER 4. SENSOR DATA ANALYTICS FOR WELLNESS DETERMINATION OF AN ELDERLY PERSON .............................................................. 79

CHAPTER 5. ADLs RECOGNITION OF AN ELDERLY PERSON AND WELLNESS DETERMINATION .......................................................... 83

5.1 Introduction ........................................................................ 83
5.2 Design of ADLs Recognition System ................................. 84
5.3 ADLs Annotation ............................................................ 85
  5.3.1 ADL Sub-Activities (Chores) Identification ..................... 87
  5.3.2 Delta Smoothing for Sub-Activities Identification ............. 91
5.4 Wellness Determination of an Elderly Person based on the usages of Household Appliances ......................................................... 92
  5.4.1 Wellness function #1 .................................................. 93
  5.4.2 Wellness function #2 .................................................. 94
  5.4.3 Need for Dynamic Wellness Functions .......................... 94
  5.4.4 Improved Wellness Function #1 .................................... 95
  5.4.5 Improved Wellness Function #2 ................................. 96
  5.4.6 Maximum Inactive and Excess Active Usage Durations (T, Tn) .... 97
CHAPTER 6. FORECASTING THE BEHAVIOUR OF AN ELDERLY PERSON USING WSN DATA

6.1 Introduction
6.2 Time Series Modeling and Forecasting
6.3 Seasonal Decomposition
6.4 Deriving Trend using Modified Double Exponential Smoothing Process
6.5 Behaviour Detection
6.6 Results and Analysis
6.7 Chapter Summary

CHAPTER 7. SENSOR ACTIVITY PATTERN (SAP) MATCHING PROCESS AND OUTLIER DETECTION

7.1 Introduction
7.2 Sensor Activity Pattern (SAP) Algorithm
  7.2.1 Notations and Definitions of the SAP Algorithm
7.3 Results and Analysis
7.4 Sensor Activity for ADL Pattern Discovery
7.5 Outlier Detection
7.6 Chapter Summary

CHAPTER 8. CONCLUSION AND FUTURE WORKS

8.1.1 Further Works

BIBLIOGRAPHY
List of Publications, Contributions and Achievements during the PhD study (2011-2014)

Awards/Recognition:
1. Recipient of Massey University doctoral scholarship for three years (Aug-2011 to Jul-2014).
3. Selected as one of the 10 finalists to the Best Student Poster Award of the IEEE - I2MTC 2013 held at Minneapolis, MN, USA, May 6-9, 2013.
4. Selected (as one of six papers) for the special issue as extended paper presented at International Conference on Intelligent Environments (IE’12), 2012, Guanajuato, Leon-Mexico.

Journal/Magazine Publications: (6)
1. Suryadevara N.K, Mukhopadhyay S.C, “Determination of Wellness of an Elderly in an Ambient Assisted Living Environment,” Accepted for publication in IEEE Intelligent Systems-May 2014, (Acceptance rate for manuscripts is under 10%, 5 Yr Impact Factor: 2.538) (Thomson Reuters(SCI)-World’s leading journals Review)


**Book Chapters: (5)**


**Google Scholar Citations:**
http://scholar.google.co.nz/citations?hl=en&user=S28OdGMAAAM
**Significant Contributions/achievements**

**IEEE Sensors Journal Top 25 Download**


**Elsevier: Most Downloaded Engineering Applications of Artificial Intelligence Articles**

Article titled: “Forecasting the behavior of an elderly using wireless sensors data in a smart home” Elsevier: Engineering Applications of Artificial Intelligence, Vol: 26, Issue: 10, Page(s): 2641-2652, 2013, has been one of the most downloaded articles in the month of March-2014.

**Tutorial Offered**

1. Practical demonstrations on design and development of Wireless Sensing system and the Graphical User Interface system was delivered at 5th International Conference on Sensing Technology, Nov. 28th - Dec. 1st, 2011, Palmerston North, New Zealand.

2. Practical demonstrations on design and development of Wireless Sensing system Graphical User Interface system was delivered at 6th International Conference on Sensing Technology, Dec.18 - Dec.21, 2012, Kolkata, India.

3. Practical demonstration on the application of wireless sensor network was delivered at IEEE-I2MTC-2014 conference May 11-14, 2014 held at Montevideo, Uruguay.

**Keynote Talk**

On Behalf of Prof.S.C.Mukhopadhyay a Keynote talk was delivered at 4th International Conference on Signal and Image Processing (ICSIP) held at Coimbatore, Tamilnadu–India -13 to 15 December-2012. Title of the talk: “Are WSN Assisted Homes Safer for the Elderly? A Smart Signal Processing Perspective”, Date: 13-Dec-2012.

**News Letter Articles**


**In News:** [http://telecommunications.verticalnews.com/articles/7081324.html](http://telecommunications.verticalnews.com/articles/7081324.html)
Date: 06-Jun2-2012, Vertical News: Telecommunication: Study Data from Massey University Update Knowledge of Sensor Research.
Seminars/Presentations

I have presented my research outcomes in the following occasions:

**Special Presentations:**

1. Title: Wellness determination of an elderly using Wireless Sensors Data in a Smart Home  
   Date: 03-May-2013  
   Venue: Electrical and Computer Engineering Department  
   College of Engineering, University of Missouri, Columbia, MO, USA

2. Title: Wireless Sensing System for Elderly Independent Living  
   Date: 01-May-2013  
   Venue: The Aware Home Research Initiative  
   479 10th st NW, Atlanta, GA 30318, USA

3. Title: Applying SARIMA Time Series to Forecast Sleeping Activity for Wellness-Model of Elderly Monitoring in Smart Home  
   Date: 18-Feb-2013  
   Venue: IEEE-I&M Chapter-NZ  
   Workshop on Smart Sensors - Instrumentation and Measurement  
   University of Waikato, Hamilton-New Zealand

4. Title: Time Series Analysis of Sensing Data for Smart Home  
   Date: 11-April-2012  
   Venue: IEEE-I&M Chapter-NZ  
   Workshop on Smart Sensors Measurements and Instrumentation: Applications to agricultural and environmental monitoring  
   Lincoln University, Christchurch-New Zealand

**Conference Presentations: (Oral)**

1. Title: Wellness determination of inhabitant based on daily activity behaviour in real-time monitoring using Sensor Networks  
   Date: 30-Nov-2011, Venue: IEEE-Fifth International Conference on Sensing Technology (ICST), 2011, Massey University-Palmerston North, New Zealand

2. Title: Intelligent Sensing Systems for measuring Wellness Indices of the Daily Activities for the Elderly (Doctoral Colloquium)  

3. Title: Applying SARIMA Time Series to Forecast Sleeping Activity for Wellness Model of Elderly Monitoring in Smart Home  
   Date: 18-Dec-2012, Venue: IEEE-6th International Conference on Sensing Technology (ICST), Kolkata, India- 2012

4. Title: Ambient Assisted Living Framework for Elderly Wellness Determination through Wireless Sensor Scalar Data  
   Date: 04-Dec-2013, Venue: IEEE-7th International Conference on Sensing Technology (ICST), Wellington-NZ-2013

5. Title: Performance Measurement in Wireless Sensor Networks using Time-Frequency Analysis and Neural Networks  
   Date: 15-May-2014, Venue: IEEE-I2MTC-2014, Montevideo, Uruguay
Poster presentation:
Title: Reliable Measurement of Wireless Sensor Network Data for Forecasting Wellness of Elderly at Smart Home
Date: 07-May-2013.

Contribution to the post graduate student thesis supervision’s

I have contributed to the supervision of the following students while they were studying under Prof. S.C. Mukhopadhyay, SEAT, Manawatu Campus, Massey University-New Zealand.

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Degree, Year</th>
<th>Thesis Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anuroop Gaddam</td>
<td>Ph.D., 2012</td>
<td>Wireless Sensor Network Based Smart Home for Elder Care</td>
</tr>
<tr>
<td>Tauseef Qazi</td>
<td>Master, 2012</td>
<td>Sensors System for Emotion Recognition</td>
</tr>
<tr>
<td>Sean Kelly</td>
<td>Master, 2013</td>
<td>Design and Implementation of Internet of Things for Home Environment</td>
</tr>
<tr>
<td>Vinok Verma</td>
<td>M.Eng. Studies, 2014</td>
<td>Data Fusion from two communication protocols</td>
</tr>
<tr>
<td>Mohammed Serhan Al Ghamdi</td>
<td>PG. Diploma, 2012</td>
<td>Medicine Dispenser for Eldercare</td>
</tr>
<tr>
<td>Hatim Al Abri</td>
<td>Bachelor Honours, 2012</td>
<td>Smart Wireless Environmental Sensing Station</td>
</tr>
<tr>
<td>MunHaw Kam</td>
<td>Bachelor Honours, 2013</td>
<td>WSN based Smart Grid for Utility System</td>
</tr>
<tr>
<td>Manaseh Togagi</td>
<td>Bachelor Honours, 2014</td>
<td>WSN and IoT in relation to a Tourist Perspective</td>
</tr>
</tbody>
</table>
Congratulations
N. K. Suryadevara
WINNER
Best Student Paper 2013
Presented at the HINZ Conference & Exhibition
27th November, 2013
March 11, 2013

TO:
Mr. Nagender Kumar Suryadevara, Massey University, New Zealand
Dr. Subhas Chandra Mukhopadhyay, Massey University, New Zealand

Dear Mr. Suryadevara and Dr. Mukhopadhyay:

On behalf of the IEEE Sensors Council I am pleased to congratulate you, the coauthors of the paper Wireless Sensor Network Based Home Monitoring System for Wellness Determination of Elderly, IEEE Sensors Journal, Vol. 12, No. 6, June 2012, for your paper being one of the 25 most downloaded Sensors Journal papers for 8 out of 12 months in 2012. It is exciting to note that included in this count are all Sensors Journal papers published since its foundation, about 1000 papers in total. You can view the latest Top 25 papers at:


Thank you for your contribution to the IEEE Sensors Journal!

Best regards,

Vladimir Lumelsky
List of Figures

Figure 1-1 Main Functional Blocks of a Home Monitoring System for a Health Informatics System .............................................................................................................................. 3
Figure 1-2 Functional Description of the Developed Smart Home Monitoring System 6
Figure 2-1 Increasing Trend of the Elderly (Aged 65+ years) Population ............ 13
Figure 2-2 Basic Components of the SHMS ......................................................... 16
Figure 2-3 Interconnection among the components of the SHMS ..................... 16
Figure 2-4 Sensor Platform with RFID Components [48] ............................. 19
Figure 2-5 One of the Test-Bed Sensor Installation of CASAS Project [58] ......... 21
Figure 2-6 Block Structure of the Residential Elder Care Monitoring System [64] ..... 22
Figure 2-7 Ubiquitous Healthcare House Monitoring Systems [69] ................. 22
Figure 3-1 Architecture of the developed WSN based Home Monitoring System .... 37
Figure 3-2 Fabricated electrical sensing system (at our laboratory) to monitor and control household electrical objects ............................................................. 39
Figure 3-3 Electrical sensing system GUI running at the base station of the WSN .... 40
Figure 3-4 Fabricated Wireless Electrical Sensing Systems attached to various Household Appliances ................................................................. 41
Figure 3-5 Fabricated Wireless Force Sensing Systems Connected to Various Domestic objects ................................................................. 42
Figure 3-6 Fabricated Wireless Sensing Systems attached to doors of Grooming table cabinet and Refrigerator ................................................................. 43
Figure 3-7 Fabricated Wireless PIR (motion) Sensing Systems ......................... 44
Figure 3-8 Fabricated Environmental Wireless Sensing System .................... 45
Figure 3-9 GUI of the Environmental Parameters Monitoring system ............. 45
Figure 3-10 Wireless Physiological Parameters Monitoring System .......... 46
Figure 3-11 Screenshot of the remote ZigBee (XBee) Module Configuration ...... 49
Figure 3-12 2D-View of the house and the placement of different Sensing Systems . 49
Figure 3-13 3D-View of the house and the placement of the domestic objects ...... 50
Figure 3-14 GUI of the HMS displaying the frequency usage of various domestic appliances ................................................................. 50
Figure 3-15 Block Diagram Showing the Required Number of Sensing Systems for monitoring the behaviour of an elderly person .............................................. 51
Figure 5-9 Sensor activity status at various subject locations ......................................... 98
Figure 5-10 Number of sensor events at different subject houses ................................... 99
Figure 5-11 Sensing units connected to household appliances usages .............................. 99
Figure 5-12 $\beta_{1,old}$ at four different elderly houses ................................................... 102
Figure 5-13 Graphical representation of $\beta_{2,old}$ Values at different elderly houses . 102
Figure 5-14 ADLs instances at two different subject locations during the trial run of
the HMS ..................................................................................................................... 105
Figure 6-1 Functional blocks of Time Series Data Mining (TSDM) ......................... 109
Figure 6-2 Subject #1: Bed usage durations and its trend ............................................. 112
Figure 6-3 Subject #1: Toilet usage durations and its trend ........................................... 113
Figure 6-4 Subject #1. Dining chair usage durations and its trend .............................. 113
Figure 6-5 Residual autocorrelations and partial autocorrelation function of time
series of the sensing durations for Dining Chair usage durations ............................. 114
Figure 6-6 Residual autocorrelations and partial autocorrelation function of time
series of the sensing durations for Bed usage durations .......................................... 115
Figure 6-7 Eight week sleeping observations and Ninth week predicted sleeping
durations .................................................................................................................... 117
Figure 6-8 K-S test result for Normal distribution of predicted sleeping durations .. 118
Figure 6-9 Toilet usage trend and tenth week forecast pattern ................................... 120
Figure 6-10 Dining chair usage and Ninth Week Forecast pattern .............................. 121
Figure 7-1 Domestic object sensor activities at different times in a day at an elderly
person house ............................................................................................................. 127
Figure 7-2 Sensor Activity Pattern Tree ..................................................................... 130
Figure 7-3 Placement of the PIR sensing systems inside the home ............................ 131
Figure 7-4 Movements of a subject on a particular day as shown on the webpage ... 131
Figure 7-5 Database file of PIR sensing systems data ............................................. 132
Figure 7-6 Fragment of the sequence of PIR sensors at a particular hour of the day 133
Figure 7-7 Frequent patterns (rules) of PIR Sensor ID’s on the Tuesdays movements
in the form of graph representation and the concentration of sensor IDs .............. 134
Figure 7-8 Frequent patterns (rules) of PIR Sensor ID’s based on the Tuesdays
movements - Grouped matrix representation ......................................................... 134
Figure 7-9 Sensor sequence at a time slot during different days of a week ............... 136
List of Tables

Table 2-1 Sensing types, parameters and applications ................................................. 17
Table 2-2 Features of Wireless Communication Technologies [44] ........................... 18
Table 2-3 Smart Home Monitoring Systems based on the importance of
communication medium .................................................................................................. 23
Table 2-4 Comparisons of various sensor data analysis related to ADLs recognition in
SHMS ............................................................................................................................. 28
Table 3-1 Frequency of Sensor Usages ....................................................................... 51
Table 3-2 Sensing Systems XBee Pin I/O Data Types ................................................ 60
Table 3-3 Sampling rates of the Sensing Systems ....................................................... 61
Table 3-4 Reliability of the wireless sensor network data transmission for different
hops ................................................................................................................................ 65
Table 3-5 Wireless Sensing System packet lengths ..................................................... 66
Table 3-6 Top 4 queries execution on the sensor database .......................................... 69
Table 5-1 Labelling process during run time of the system .......................................... 89
Table 5-2 ‘T’ values of various objects usages at sub#1 home for a week .......... 100
Table 5-3 (β2,old) values of various objects usages at sub#1 home ....................... 100
Table 5-4 (β2,old) values of various objects usages at sub#2 home ....................... 101
Table 5-5 (β2,old) values of various objects usages at sub#3 home ....................... 101
Table 5-6 Improved Wellness Functions Calculations .............................................. 104
Table 6-1 Prediction of 9th week Bed, Toilet and Dining Chair usage durations based
on SARIMA process ..................................................................................................... 116
Table 6-2 Wellness function indices of household appliances and forecast of the
ADLs .............................................................................................................................. 122
Table 7-1 Sensor Activity Pattern (SAP) Algorithm ................................................. 129
Table 7-2 Sensor Sequence Pattern Meaning ............................................................ 133
Table 7-3 I/O files snapshot of the household objects sensor sequences to recognize
the ADL patterns ............................................................................................................ 136
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAL</td>
<td>Ambient Assisted Living</td>
</tr>
<tr>
<td>ADL</td>
<td>(Basic) Activities of Daily Living</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Network</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things</td>
</tr>
<tr>
<td>HMS</td>
<td>Home Monitoring System</td>
</tr>
<tr>
<td>SHMS</td>
<td>Smart Home Monitoring System</td>
</tr>
<tr>
<td>SAP</td>
<td>Sensor Activity Pattern</td>
</tr>
<tr>
<td>PSN</td>
<td>Pervasive Sensor Network</td>
</tr>
<tr>
<td>PAI</td>
<td>Predictive Ambient Intelligence</td>
</tr>
<tr>
<td>PIR</td>
<td>Passive-Infra Red</td>
</tr>
<tr>
<td>The Elderly</td>
<td>A person aged above 65 years</td>
</tr>
<tr>
<td>An Elderly person</td>
<td></td>
</tr>
</tbody>
</table>