The Device Free Localization Algorithm for Indoor Detection and Tracking of Living Entities

by

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Shaufikah Shukri

TABLE OF CONTENTS

CHAPTER 2 : LITERATURE REVIEW 19

LIST OF TABLES

PAGE

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAL	Ambient Assisted Living
aDFL	attenuation-based DFL
ANN	Artificial Neural Network
AoA	Angle of Arrival
AoI	Area of Interest
AS	Application Server
CEASTech	Centre of Excellence for Advanced Sensor and Technology
CS	Compressed Sensing
CST	Microwave Studio Software
daDFL	directional attenuation-based DFL
DFL	Device-Free Localization
DfP	Device-free Passive
DL	Deep Learning
DNN	Deep Neural Network
dRTI	directional RTI
ED	Energy Detection
EI	Embedded Intelligence
EM	Electromagnetic Wave
ESD	Electronically Switched Directional
ESPAR	Electrically-Steerable Parasitic Array Radiator
EWMA	Exponentially Weighted Moving Average
FMS	Finite State Machine
GPS	Global Positioning System
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
ID	Identification
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IR	Infrared
ISM	Industrial, Scientific, and Medical
ISP	In-System Processor
KLD	Kullback-Leibler Divergence
LBS	Location-based Services

LED	Light-emitting Diode
LoS	Line-of-Sight
LTH	Long-term Histogram
maDFL	modified attenuation-based DFL
MIMO	Multiple-Input Multiple-Output
MLP	Multi-Layer Perceptron
MSE	Mean Squared Error
NHS	National Health Service
NLoS	Non Line-of-Sight
OQPSK	Offset Quadrature Phase Shift Keying
PC	Personal Computer
PCA	Principal Component Analysis
pDFL	Probabilistic-radio map-based DFL
PIR	Passive Infrared
PoE	Probability of Error
PRR	Packet Reception Rate
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio-Frequency Identification
RMSE	Root Mean Squared Error
RNN	Recurrent Neural Network
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RTI	Radio Tomography Imaging
Rx	Receiver
SMC	Sequential Monte Carlo
SOF	Special Operations Forces
STH	Short-term Histogram
SVM	Support Vector Machine
SWAT	Special Weapons and Tactics
TDoA	Time Difference of Arrival
ToA	Time of Arrival
Tx	Transmitter
UNB	Ultra-Narrowband

UniMAP	University of Malaysia Perlis
USB	Universal Serial Bus
UWB	Ultra-wideband
vDFL	variance-based DFL
WHO	World Health Organization
Wi-Fi	Wireless Fidelity
WSN	Wireless Sensor network

LIST OF SYMBOLS

D	Directivity
dB	Decibel
dBm	Decibel-Milliwatts

Algoritma bagi Sistem Penentuan Lokasi Tanpa Peranti untuk Mengesan dan Menjejaki Entiti Hidup di dalam Bangunan

ABSTRAK

Kebanyakan kajian mengenai sistem penentuan lokasi tanpa peranti telah dijalankan dalam pengaturan makmal yang terkawal, lalu menyekat ketersediaan set data. Namun begitu, kajian dalam senario sebenar adalah lebih mencabar disebabkan faktor persekitaran luar kawalan seperti jenis binaan bangunan, keadaan cuaca, dan pergerakan objek serta entiti hidup. Kajian terdahulu dilaksanakan dalam kawasan berskala kecil serta menggunakan rangkaian Wi-Fi untuk pengesanan, dimana rangkaian ini berisiko mengalami gangguan penyambungan. Penggunaan peranti tanpa wayar seperti IRIS yang menggunakan teknologi rangkaian sensor tanpa wayar mampu mengatasi cabaran ini. Selain itu, tubuh manusia turut memberi kesan terhadap penyebaran isyarat frekuensi radio, dimana pergerakan dan kehadiran manusia mampu mengubah kekuatan isyarat radio kerana tubuh manusia mengandungi cecair yang boleh mengganggu isyarat radio. Selain itu, isyarat frekuensi radio boleh menembusi halangan seperti dinding dan perabot, sekaligus mengurangkan kesalahan pengesanan palsu. Oleh itu, kajian menyeluruh diperlukan untuk memahami perilaku isyarat frekuensi radio dalam senario yang melibatkan kehadiran satu entiti hidup menggunakan sistem persediaan yang dibangunkan. Perbandingan ketepatan algoritma sedia ada sukar untuk dibuat kerana terdapat perbezaan pada pendekatan pembangunan. Dengan itu, adalah penting untuk membangunkan dan menguji algoritma baharu bagi sistem penentuan lokasi tanpa peranti menggunakan reka bentuk dan persediaan yang dilaksanakan. Bagi meningkatkan ketepatan dan prestasi algoritma sedia ada, maklumat kajian seperti spesifikasi pelaksanaan, butiran perkakasan, protokol komunikasi dan set data, perlu dikongsi secara terbuka. Oleh itu, kajian ini bertujuan membangunkan sistem penentuan lokasi tanpa peranti untuk mengesan dan menjejak kehadiran manusia di dalam bangunan berdasarkan perubahan pada kekuatan isyarat frekuensi radio. Ujian pencirian isyarat frekuensi radio telah dijalankan untuk mengenal pasti kesan kehadiran manusia terhadap kekuatan isyarat pautan rangkaian tunggal, dan nilai purata pengecilan isyarat frekuensi radio. Keputusan ujian perincian menunjukkan profil isyarat radio mengalami perubahan kesan daripada kehadiran manusia dengan nilai purata pengecilan sebanyak 3.97 dBm. Kekuatan isyarat radio didapati mengalami perubahan dengan kehadiran manusia pada jarak sekurang-kurangnya 1.0 m dari garis lintas pautan rangkaian, manakala pergerakan manusia merentasi garis lintas tersebut menghasilkan pengecilan isyarat antara 10 hingga 15 dBm. Beberapa jenis algoritma telah dibangunkan dan diuji bagi tujuan pengumpulan data, iaitu berasaskan pengecilan, berasaskan varians, berasaskan pengecilan berarah, berasaskan pengecilan yang diubahsuai, berasaskan kebarangkalian pemetaan radio, berasaskan rangkaian saraf buatan dan rangkaian saraf mendalam. Prestasi setiap algoritma yang dibangunkan dinilai dan dibandingkan menggunakan bacaan ketepatan dan ralat. Rangkaian saraf mendalam yang dicadangkan dikenalpasti sebagai algoritma yang sesuai untuk mengesan dan menjejak entiti hidup di dalam bangunan berskala besar, iaitu dengan ketepatan sebanyak 0.910, tanpa mengalami masalah kerumitan algoritma dan ketumpatan pautan rangkaian.

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ABSTRACT

Most research on device-free localization techniques has occurred in controlled lab settings, limiting the availability of dataset. However, research in real-world scenarios is more challenging due to uncontrollable environmental factors such as building structures, weather conditions, and the movement of objects and living entities. Prior studies often used small-scale lab setups with dense nodes, mainly relied on Wi-Fi networks and hardware for detection, posing the risk of connection disruptions. Using easy-to-use wireless devices like the IRIS by MEMSIC, which utilizes wireless sensor network technology, helps overcome these challenges. Additionally, the human body affects radio frequency signal propagation. Human movement and presence can alter signal strength since the human body contains water, interferes with radio frequency signals. Radio frequency signals are beneficial in low-light areas and can penetrate obstacles like walls and furniture, reducing false detections and system issues. Therefore, a comprehensive study is necessary to understand radio frequency signal behavior in scenarios involving one person using deployed setups. Comparing the accuracy of existing device-free localization algorithms is difficult due to differences in development approaches. To overcome these challenges, it is essential to develop and test new algorithms using deployed setups to gather thorough datasets. To enhance the accuracy and performance of existing algorithms, research information such as implementation specifications, hardware details, communication protocols, and datasets should be openly shared. Hence, this study aims to develop new algorithms capable of detecting and predicting the location and movement of humans in a building based on changes in radio frequency signal strength, using wireless sensor network technology. The radio signal characterization test was conducted to examine the impact of the human body on the signal strength of a single network link, as well as to determine the average signal fluctuation in the presence of a human body on the network. The radio signal profile is observed to fluctuate by an average of 3.97 dBm in the presence of a human body, whether positioned directly in the line-of-sight or in close proximity to the network link. The human body has an impact on the signal strength when located at a distance of at least 1.0 m from the line-of-sight link. Meanwhile, human movement across the line-of-sight link can induce significant signal variations, ranging between 10 dBm and 15 dBm. New device-free localization algorithms based on statistical and neural network approaches have been developed, including attenuation-based, variance-based, directional attenuation-based, modified attenuation-based, probabilistic radio mapping, Artificial Neural Network-based, and Deep Neural Network-based methods. A series of experimental tests were conducted to collect datasets for both small-scale and large-scale implementation setups. The performance of each developed algorithm was evaluated and compared using accuracy and loss metrics. Based on the observation results, the Deep Neural Network-based algorithm was identified as suitable for localizing and tracking living entities in larger areas, achieving an accuracy of 0.910 without encountering algorithmic complexity or link density issues.

CHAPTER 1 : INTRODUCTION

1.1 Human Localization System Overview

The remarkable advancements in medicine, science, and technology have resulted in a significant rise in the average human lifespan, leading to a global increase in the aging population. People are becoming healthier and living longer, contributing to this phenomenon. According to He *et al.* (2016), in 2012, 8.0% (or 562 million) of the global population of 7 billion were aged 65 and above. Based on current trends, it is projected that the elderly population will rise by up to 17% (or 1.6 billion) worldwide by 2050. Consequently, the increasing number of older individuals has had a modest impact on the disability rates among the world population (WHO, 2018). What is more worrying is that most of elderly are unable to maintain healthy behaviours throughout their extra life span. Consequently, they are more prone to developing age-related diseases and disabilities, affecting their physical and mental functions.

Human localization has garnered significant attention from the research community, particularly for Ambient Assisted Living (AAL) applications. Human localization is an important yet challenging research topic which emphasizes on detecting, tracking and localizing the location of living entities in the indoor environment using wireless sensor network (WSN). The research community has shown considerable interest in this topic lately due to the progress made in information and communication technology (ICT) and WSN technologies. In earlier work, a human localization system was introduced for detecting and locating the human position in either indoor or outdoor designated areas. The need for applications of indoor human localization is continuously being explored and acquiring reasonable importance, especially for AAL applications.

Moreover, the majority of elderly individuals prefer to live independently in their own homes (Farber *et al.*, 2011). With conventional methods of elderly care proving less effective in modern society, there is a growing demand for assistive technologies that allow families to respectfully monitor their loved ones even when they live separately.

Additionally, many elderly individuals face financial constraints, making it challenging to afford healthcare expenses and expensive private nursing home care services, especially with lower income after retirement. The conventional approach for detecting and recognizing humans in security systems relies on vision-based or video camera techniques. However, video cameras have limitations in low-light conditions and restricted viewing angles. To overcome these drawbacks, Passive Infrared (PIR) sensors are commonly employed in motion detection systems. PIR sensors detect the thermal radiation emitted by moving subjects, enabling the sensing of human, animal, or object movements. Nevertheless, PIR sensors are susceptible to false detections caused by warm airflows from sources such as air conditioners and radiators. Ultrasonic motion sensors which are often used in the measurement of distance, are also prone to false detection due to the sensitivity of ultrasound wave measurement which might respond to the external noise from surroundings such as vehicles and electronic devices. False detection events can cause system disruptions and result in human discomfort.

Preliminary works on localization or location estimation using WSN began in environmental monitoring applications such as habitat monitoring (Mainwaring *et al.*, 2002), forest-fire surveillance (Son *et al.*, 2006), water quality monitoring (O'Flynn *et al.*, 2007) and precision agriculture (Zhang, 2004; Baggio, 2005). Youssef *et al.* (2007) were regarded as pioneers in the field of device-free localization (DFL) system in wireless environments when they introduced the concept in 2007. Since then, significant progress has been made in research on human location estimation using WSN, with active discussions focusing on the DFL research directions and challenges.

Subsequently, there has been a significant research effort directed towards device-free human localization, particularly in indoor environments, owing to its simplicity, less costly and compatibility. Tremendous research works have been published, presenting various types of algorithms, wireless network technologies and hardware approaches for AAL applications with high reliability, low-cost, low-power, device-free systems in performing real-time human monitoring. Most of existing device-free localization systems are developed using the existing commercial WSN motes such as MICA, IRIS, TelosB, etc., which are known for being both low-cost and low-power devices. Researchers encounter a significant challenge in dealing with the inherent hierarchical structure of human movement and behaviour while performing daily activities. Or in simpler words, each individual possesses a unique pattern of movement and behaviour. Meanwhile, the existing occupancy sensor technologies that required user involvement are not very practical, especially for locating and monitoring elderly, disabled people and children.

This thesis intends to develop a human localization system that should have at least the following three equally important and promising features.

a. *Device-free*, where the system does not require users to wear or carry any special sensor that might cause physical discomfort. Active participation in the localization process is not necessary for users; in other words, they are typically unaware of the system's presence.

b. *Smart and Intelligent*, where the system should be capable of updating or adjusting itself in response to changes in the environment, comprehend and recognize the regular patterns and habits of the user, and accurately identify any abnormal events by analysing the results obtained from its detection capabilities. This clarifies that the system is designed to be dynamic, user-aware, and adept at identifying anomalies based on collected data. Any irregular patterns of activities will indicate abnormal events. For instance, spending more time in bed than usual sleeping hours may indicate that the person is unwell. Alternatively, sudden changes in signal patterns while the user is in the kitchen or bathroom may suggest that the user has fallen. Thus, the system notifies family members of the user about the user's condition.

c. *Unintrusive*, where the system can be installed in any location within the building without causing privacy concerns, particularly in private spaces like lavatories, bathrooms, bedrooms, and nursing rooms.

In the modern era, there exists an extensive network of interconnected objects, either through wired or wireless connections, that are linked to the physical world. According to Vermesan & Friess (2014), the number of wireless devices connected to the internet had already surpassed the global human population in 2011, and it was projected to grow further to a range of 26 billion to 50 billion devices by the year 2020. Thanks to the development and sophistication of technology, especially in the ICT area, things and objects that human use every day become smarter due to the availability of internet connection, which results in high demand for potential smart applications with the aim to improve the quality of human lives. The ubiquity of these everyday devices, coupled with advancements in wireless technologies and internet integration, has ushered in a world where interconnected smart devices coexist. This phenomenon is widely known as the Internet of Things (IoT).

1.1.1 Internet of Things (IoT)

With significant advancement of sensing, wireless communication, and Internet technologies, humans are now living in a world that is filled with various smart things that are connected together to form a network called the Internet of Things (IoT). The basic concepts of IoT are the transformation of everyday devices into smart objects, which are capable of recognizing, interpreting, acting and reacting to the environment in an appropriate way without human intervention, by utilizing the embedded technology (Domingo, 2012). With the primary objective of enhancing the quality of human lives, the IoT serves as a bridge between the virtual and physical realms. It achieves this by creating smart environment applications that are accessible through various devices. In essence, the integration of IoT brings about a transformation of the physical world into an information and intelligence system, leading to significant improvements in real-world scenarios and enhancing people's daily lives, particularly in terms of time and resource conservation. The introduction of IoT-enabled products and services, such as home automation components, internet-connected appliances, and energy management devices, has revolutionized the manual aspects of everyday home environments. These advancements have turned homes into automated and intelligent environments, offering enhanced security and improved energy efficiency, thus leading to a better quality of life.

Since the term was first introduced by Kevin Ashton in 1998 (Bandyopadhyay & Sen, 2011), the research domains of the IoT have proliferated and found wide-ranging applications in various industries. These industries include telecommunications (Wollschlaeger, Sauter & Jasperneite, 2017), transportation systems, and manufacturing (Mourtzis, Vlachou & Milas, 2016; Caputo, Marzi & Pellegrini, 2016), home automation (Gaikwad, Gabhane & Golait, 2015), aerospace and aviation (Ning *et al.*, 2012; Ramalingam, Christophe, & Samuel, 2017), medical and healthcare (Islam *et al.*, 2015; Ullah, Shah, & Zhang, 2016), food industry (Ying & Fengquan, 2013), agriculture (Tzounis *et al.*, 2017; Zhang, Dabipi & Brown Jr, 2018), environmental monitoring (Kanagaraj *et al.*, 2015; Montori, Bedogni & Bononi, 2017), security surveillance (Ding *et al.*, 2018; Panchatcharam & Vivekanandan, 2019), and other sectors. To date, research works on the IoT-based potential applications are still in full swing and are becoming increasingly popular due to the sophistication of ICT technology.

1.1.2 Wireless Sensor Networks Technology

Motivated by numerous theoretical and practical challenges, wireless sensor networks (WSNs) have garnered significant attention from the research community over the past two decades. In essence, a WSN is a network comprising a multitude of distributed and dedicated low-power sensor nodes that are interconnected wirelessly. These nodes possess the capability to sense, compute, communicate, observe, and respond to event scenarios in specific environments. According to Zhang & Zhang (2012), the applications of WSN can be classified into two categories: