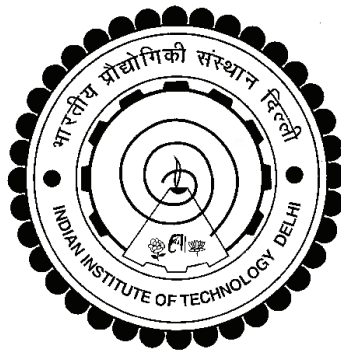


PERSON IDENTIFICATION THROUGH FOOTSTEP-BASED BIOMETRIC RECOGNITION

SAHIL ANCHAL



**BHARTI SCHOOL OF TELECOMMUNICATION
TECHNOLOGY AND MANAGEMENT**

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JANUARY 2024

PERSON IDENTIFICATION THROUGH FOOTSTEP-BASED BIOMETRIC RECOGNITION

by

SAHIL ANCHAL

**BHARTI SCHOOL OF TELECOMMUNICATION TECHNOLOGY
AND MANAGEMENT**

Submitted

*in fulfilment of the requirements of the degree of Doctor of Philosophy
to the*



**INDIAN INSTITUTE OF TECHNOLOGY DELHI
JANUARY 2024**

This dissertation stands as a profound tribute to
the cherished memory of my dear father, late Praduman Kumar
and my beloved grandfather(Nana ji), late Basant Ram, honouring their indelible
legacy.

CERTIFICATE

This is to certify that the thesis titled **Person Identification Through Footstep-Based Biometric Recognition**, submitted by **Sahil Anchal**, to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a bona fide record of his research work under my supervision.

The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. Subrat Kar

Department of Electrical Engineering &
Bharti School of Telecommunication Technology and Management
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, INDIA

Place: New Delhi

ACKNOWLEDGEMENTS

I am profoundly grateful to the remarkable individuals who have played an integral role in making this thesis a reality. Their unwavering support, guidance, and encouragement have been instrumental throughout my journey.

First of all, my most sincere thanks to my supervisor, Prof. Subrat Kar, for accepting me as his PhD student and for his consistent support and supervision throughout the course. I have been extremely fortunate to have a supervisor who encouraged me at every stage and showed me the right path in fulfilling my endeavours. Under his mentorship, I have learnt how to learn things, which has made me fearless in the sense that I am no longer hesitant or afraid of at least trying out new things, and this has given me a strange sense of confidence that I can now do anything.

I would like to express my deep gratitude to the members of my SRC committee, Prof. Sumantra Dutta Roy (Chairman), Prof. Brejesh Lall (Department Expert), and Prof. Bhawani Shankar Panda (External Expert). Their invaluable contributions and critical evaluation of my research work have been instrumental in refining and enhancing the quality of my thesis. I am sincerely thankful for their expertise, guidance, and constructive feedback, which have greatly influenced the outcome of my research.

I would also like to express my sincere gratitude to Prof. Dhanya C.T. from the Civil Engineering Department for the financial support; her generosity and encouragement have been invaluable.

I am extremely grateful to Dr Bodhibrata Mukhopadhyay for his consistent help and support throughout my research journey. His expertise and guidance have been invaluable in shaping my work. I am thankful for his valuable insights and unwavering encouragement that have significantly contributed to the success of my dissertation. I am also grateful to my colleagues, Mr Manohar Kumar Parvatini, Mr Ved Singh, Mr Nikhil Parashar, Mr Sandeep Sharma, Dr Prerna Mukherjee, Mr Manoj Sharma, Ms Sonal Gupta, Dr Vipul Sharma(PhD, JNU), Mr Chandan Kumar, Mr Mainak Chakraborty, Mr Animesh Chattopadhyaya, Ms Aradhana Mishra, Rev. Karandagolle Wijithatissa(Senior

Lecturer, Bikshu University of Sri Lanka) and all the students of the M.Tech JTM 2018-20 batch, for their camaraderie and intellectual exchanges. I am indebted to Mr Prateek Yadav for engaging in discussions and thought-provoking debates, both within and beyond the realms of our research.

I would like to express my gratitude to Mrs Sagarika Dutta Bishwas and Mr Gundee for their unstinting assistance in administrative matters. I am also thankful to Dr Shekhar Jain, PhD (JNU), for his keen interest in my research, insightful discussions, and uplifting words of encouragement.

To my friends, Mr Karan Agarwal, Mr Rohit Goyal, Mr Amit Ranjan, Mr Devesh Rawat and Aakash Sagar, and Mr Vivek Choudhary(Vicky), I am truly grateful for pulling me out of the lab on weekends and for reminding me of the importance of rejuvenation and leisure activities.

I owe a debt of gratitude to my family members for their consistent and unconditional support throughout this journey. My heartfelt thanks to Smt. Rajkumari (Mother), Smt. Pushpa Devi (Massi/Aunt), my elder brother, Mr Shani Anchali, and sister-in-law, Mrs Sapna Bahari. I am also blessed to have the love and affection of my adorable niece and nephew, Miss Shivanshi Choudhary and Master Ganu, and my younger brother, Mr Shubham Anchali.

Lastly, I would like to thank Mr Manoj Rana and Mr Rajkumar for their encouraging words and assistance with technical and logistical matters.

I am also grateful to the Bharti School of Telecommunication Technology and Management office staff, IIT Delhi, for providing the necessary resources and logistical support to make this research possible.

Words cannot express my appreciation for all these remarkable individuals. Without their unwavering support and contributions, this thesis would not have been possible.

Sahil Anchali

January 2024

ABSTRACT

There is significant interest in person identification using seismic data from the foot steps as a biometric modality. As a biometric for person identification, footsteps offer benefits over conventional biometric modalities such as facial images, speech signals, fingerprints and IRIS inter alia. The conventional modalities are prone to unavoidable limitations – such as ambient light in the case of facial images, environmental noise in the case of speech and active co-operation of the users in the case of IRIS and fingerprint data. Also, privacy and spoofing issues are commonly encountered in these modalities. The footstep-based person identification method uses seismic sensors to record the ground or structural vibration caused by walking that involves the rhythmic contact of the toes and heels of the users with a surface. It is non-invasive and easy to use, as users have to walk past, or cross the sensing zone to register the footsteps. Moreover, the difficulty in counterfeiting the walking pattern in terms of the seismic signal makes it much more secure than its counterparts. In this thesis, we use a seismic sensor to record the footstep signals and identify walking individuals based on their footsteps.

First, we propose a novel method for person identification based on footstep-induced seismic signals for smart home applications. The person identification system is implemented in the three-layer computing architecture for the decentralised biometric system deployment. A basis pursuit-based data compression technique (DS8BP) is proposed to transmit footstep event data efficiently. We have performed extensive experimentation to evaluate the proposed biometric system using indigenous databases containing 100,000+ footfall events of eight individuals collected on different floors.

Next, we propose a novel, unconstrained biometric authentication system capable of detecting unauthorized/unregistered individuals (imposters). To mimic realistic scenarios for imposter detection, the models are trained only with the footstep data of *registered* users (footsteps of unregistered users are completely unknown/unseen to the trained models), thus achieving imposter detection for footstep-based person identifica-

tion. To validate the robustness of the proposed system, we used an indigenous curated data set containing 78000+ footstep events collected from 8 individuals on three types of surfaces (concrete tile floor, carpet floor, and wooden floor). We propose a statistical approach for person verification using Gaussian Mixture Model-Universal Background Model (GMM-UBM) to verify the registered users.

Next, we use the transfer learning approach to address the issue of distribution drift in the data set due to different deployment environments or data sets belonging to novel classes(new users). We proposed a deep learning-based class-aware, semi-supervised, and self-supervised domain adaptation technique (CA-S4DA) to address the problem of cross-domain person identification. CA-S4DA utilizes the labelled source domain data and a few labelled target domain data to learn the domain invariant feature representation while preserving the class-discriminative structure. Class-aware domain alignment is reinforced using self-supervised class-aware loss, which leverages the pseudo-labels generated from the unlabelled samples from the target domain. We have implemented and analysed the performance of our algorithms extensively and have compared CA-S4DA with state-of-the-art techniques using two indigenous data sets collected from three distinct types of floors. We also present a detailed ablation analysis to understand how each component of the proposed framework of CA-S4DA contributes to overall performance.

Finally, we propose FootsNet, a convolutional neural network(CNN) for footstep-based person identification with transfer learning, to accommodate the new users in the existing person identification. The network is trained in two stages to accommodate new users with a minimal number of labelled data.

सारांश

बायोमेट्रिक पद्धति के रूप में कदमों से भूकंपीय डेटा का उपयोग करके व्यक्ति की पहचान में महत्वपूर्ण रुचि है। व्यक्ति की पहचान के लिए बायोमेट्रिक के रूप में, पदचिह्न अन्य बातों के साथ-साथ पारंपरिक बायोमेट्रिक तौर-तरीकों जैसे कि चेहरे की छवियां, भाषण संकेत, उंगलियों के निशान और आईआरआईएस पर लाभ प्रदान करते हैं। पारंपरिक तौर-तरीके अपरिहार्य सीमाओं से ग्रस्त हैं - जैसे चेहरे की छवियों के मामले में परिवेशी प्रकाश, भाषण के मामले में पर्यावरणीय शोर और आईआरआईएस और फिंगरप्रिंट डेटा के मामले में उपयोगकर्ताओं का सक्रिय सहयोग। साथ ही, इन तौर-तरीकों में गोपनीयता और स्पूफिंग के मुद्दे भी आम तौर पर सामने आते हैं। पदचिह्न-आधारित व्यक्ति पहचान विधि चलने के कारण होने वाली जमीन या संरचनात्मक कंपन को रिकॉर्ड करने के लिए भूकंपीय सेंसर का उपयोग करती है जिसमें सतह के साथ उपयोगकर्ताओं के पैर की उंगलियों और एड़ी का लयबद्ध संपर्क शामिल होता है। यह गैर-आक्रामक और उपयोग में आसान है, क्योंकि उपयोगकर्ताओं को कदमों को दर्ज करने के लिए अतीत में चलना पड़ता है, या संवेदन क्षेत्र को पार करना पड़ता है। इसके अलावा, भूकंपीय संकेत के संदर्भ में चलने के पैटर्न को नकली बनाने में कठिनाई इसे अपने समकक्षों की तुलना में अधिक सुरक्षित बनाती है। इस शोध प्रबंध में, हम कदमों के संकेतों को रिकॉर्ड करने और उनके कदमों के आधार पर चलने वाले व्यक्तियों की पहचान करने के लिए एक भूकंपीय सेंसर का उपयोग करते हैं।

सबसे पहले, हम स्मार्ट होम अनुप्रयोगों के लिए पदचिह्न-प्रेरित भूकंपीय संकेतों के आधार पर व्यक्ति की पहचान के लिए एक उपन्यास विधि का प्रस्ताव करते हैं। विकेंद्रीकृत बायोमेट्रिक प्रणाली परिनियोजन के लिए व्यक्ति पहचान प्रणाली को तीन-परत कंप्यूटिंग आर्किटेक्चर में लागू किया गया है। फुटस्टेप इवेंट डेटा को कुशलतापूर्वक प्रसारित करने के लिए एक आधार खोज-आधारित डेटा संपीड़न तकनीक (DS8BP) प्रस्तावित है। हमने विभिन्न मंजिलों पर एकत्रित आठ व्यक्तियों की 100,000 से अधिक उपस्थिति वाले स्वदेशी डेटाबेस का उपयोग करके प्रस्तावित बायोमेट्रिक प्रणाली का मूल्यांकन करने के लिए व्यापक प्रयोग किया है। इसके बाद, हम एक नवीन, अप्रतिबंधित बायोमेट्रिक प्रमाणीकरण प्रणाली का प्रस्ताव करते हैं जो अनधिकृत/अपंजीकृत व्यक्तियों (धोखेबाजों) का पता लगाने में सक्षम है। धोखेबाज का पता लगाने के लिए यथार्थवादी परिदृश्यों की नकल करने के लिए, मॉडलों को केवल पंजीकृत उपयोगकर्ताओं के फुटस्टेप डेटा के साथ प्रशिक्षित किया जाता है (अपंजीकृत उपयोगकर्ताओं के नक्शेकदम प्रशिक्षित मॉडलों के लिए पूरी तरह से अज्ञात/अनदेखे होते हैं), इस प्रकार पदचिह्न-आधारित व्यक्ति की पहचान के लिए धोखेबाज का पता लगाया जाता है। प्रस्तावित प्रणाली की मजबूती को मान्य करने के लिए, हमने एक स्वदेशी क्यूरेटेड डेटा सेट का

उपयोग किया जिसमें तीन प्रकार की सतहों (कंक्रीट टाइल फर्श, कालीन फर्श और लकड़ी के फर्श) पर 8 व्यक्तियों से एकत्र किए गए 78000+ फुटस्टेप घटनाएं शामिल थीं।

हम पंजीकृत उपयोगकर्ताओं को सत्यापित करने के लिए गॉसियन मिक्सचर मॉडल-यूनिवर्सल बैकग्राउंड मॉडल (जीएमएम-यूबीएम) का उपयोग करके व्यक्ति सत्यापन के लिए एक सांख्यिकीय दृष्टिकोण का प्रस्ताव करते हैं। इसके बाद, हम विभिन्न परिनियोजन परिवेशों या नए वर्गों (नए उपयोगकर्ताओं) से संबंधित डेटा सेटों के कारण डेटा सेट में वितरण बहाव के मुद्दे को संबोधित करने के लिए ट्रांसफर लर्निंग दृष्टिकोण का उपयोग करते हैं। हमने गहन शिक्षण-आधारित वर्ग-जागरूक, अर्ध-पर्यवेक्षित और स्व-पर्यवेक्षित डोमेन अनुकूलन तकनीक (CA-S4DA) का प्रस्ताव दिया⁴ डीए) क्रॉस-डोमेन व्यक्ति पहचान की समस्या का समाधान करने के लिए। सीए-एस4डीए(CA-S4DA) वर्ग-भेदभावपूर्ण संरचना को संरक्षित करते हुए डोमेन अपरिवर्तनीय सुविधा प्रतिनिधित्व को सीखने के लिए लेबल किए गए स्रोत डोमेन डेटा और कुछ लेबल किए गए लक्ष्य डोमेन डेटा का उपयोग करता है। वर्ग-जागरूक डोमेन संरेखण को स्व-पर्यवेक्षित वर्ग-जागरूक हानि का उपयोग करके सुदृढ़ किया जाता है, जो लक्ष्य डोमेन से गैर-लेबल वाले नमूनों से उत्पन्न छद्म-लेबल का लाभ उठाता है। हमने अपने एल्गोरिदम के प्रदर्शन को बड़े पैमाने पर लागू और विश्लेषण किया है और सीए-एस4डीए(CA-S4DA) की तुलना की है⁴तीन अलग-अलग प्रकार के फर्शों से एकत्र किए गए दो स्वदेशी डेटा सेटों का उपयोग करके अत्याधुनिक तकनीकों के साथ डीए। हम सीए-एस4डीए(CA-S4DA) के प्रस्तावित ढांचे के प्रत्येक घटक को समझने के लिए एक विस्तृत पृथक्करण विश्लेषण भी प्रस्तुत करते हैं समग्र प्रदर्शन में योगदान देता है।

अंत में, हम मौजूदा व्यक्ति पहचान में नए उपयोगकर्ताओं को समायोजित करने के लिए, ट्रांसफर लर्निंग के साथ फुटस्टेप आधारित व्यक्ति पहचान के लिए एक कन्वेन्शनल न्यूरल नेटवर्क (सीएनएन) फूट्सनेट का प्रस्ताव करते हैं। न्यूनतम संख्या में लेबल किए गए डेटा के साथ नए उपयोगकर्ताओं को समायोजित करने के लिए नेटवर्क को दो चरणों में प्रशिक्षित किया जाता है।

Publications related to or arising from work in this Thesis

Journal Papers

1. **S. Anchal**, B. Mukhopadhyay and S. Kar, "Person Identification using Structural Vibrations via Footfalls for Smart Home Applications," in *IEEE Internet of Things Journal*, Vol. 8, No. 17, pp. 13384-13396, Sep. 2021. [Download Link]
2. **S. Anchal**, B. Mukhopadhyay and S. Kar, "Person Identification and Imposter Detection Using Footstep Generated Seismic Signals," in *IEEE Trans. on Instrumentation and Measurement*, vol. 70, pp. 1-11, 2021, Art no. 2501511. [Download Link]

Conference Papers

1. **S. Anchal**, B. Mukhopadhyay and S. Kar, "FootsNet: A Convolutional Neural Network for Footstep-based Person Identification," 2022 *IEEE SENSORS*, Dallas, Texas, USA, 2022, pp. 1-4.[Download Link]
2. **S. Anchal**, B. Mukhopadhyay, M. Parvatini and S. Kar, "GMM-UBM based Person Verification using footfall signatures for Smart Home Applications," 2019 *IEEE Global Conference on Signal and Information Processing (GlobalSIP)*, Ottawa, ON, Canada, 2019, pp. 1-5. [Download Link]
3. **S. Anchal**, B. Mukhopadhyay and S. Kar, "Person Identification and Imposter Detection using Footfall based Biometric System," 2019 *IEEE SENSORS*, Montreal, QC, Canada, 2019, pp. 1-4. [Download Link]

Manuscript communicated

1. **S. Anchal**, B. Mukhopadhyay, and S. Kar, "Footstep-based Cross-Domain Person Identification using Semi-Supervised Domain Adaptation" under review in *IEEE Transactions on Informatics and Forensics Security*

Patents filed

1. S. Kar, B. Mukhopadhyay, and **S. Anchal**. System And Method For Footstep-Based Cross-Domain Person Identification. Filled Indian patent application number 202311013308.
2. S. Kar, B. Mukhopadhyay, and **S. Anchal**. Person Identification And Imposter Detection Using Footfall Generated Seismic Signals. Filled U.S. Patent Application No. 17/112,551.
3. S. Kar, B. Mukhopadhyay, and **S. Anchal**. Person Identification And Imposter Detection Using Footfall Generated Seismic Signals. Filled Indian patent application number 201911050076.

Patent granted

1. S. Kar, B. Mukhopadhyay, and **S. Anchal**. Fog based Systems and Methods for Person Identification. Patent number: 495023, Application number: 201811016962

Publications and Patents other than the Thesis

Journal Papers

1. **S. Anchal**, B. Mukhopadhyay, and Subrat Kar. "Person Identification using Seismic Signals generated from Footfalls". In: arXiv: 1809.08783 [cs.LG]. [Download Link]
2. **S. Anchal**, B. Mukhopadhyay and S. Kar, "URED-T: Unsupervised Learning Based Real-Time Footfall Event Detection Technique in Seismic Signal," in *IEEE Sensors Letters*, vol. 2, no. 1, pp. 1-4, March 2018. [Download Link]
3. B. Mukhopadhyay, **S. Anchal** and S. Kar, "Detection of an Intruder and Prediction of His State of Motion by Using Seismic Sensor," in *IEEE Sensors Journal*, vol. 18, no. 2, pp. 703-712, 15 Jan.15, 2018. [Download Link]

Conference Papers

1. S. Kar, T.K. Mohanty, B. Mukhopadhyay, and **S. Anchal**. "Some affordable technology solutions using IoT for the small Indian farmer". In: *47th Dairy Industry Conference 2019*, pp. 100–102. [Download Link]
2. **S. Anchal**, B. Mukhopadhyay and S. Kar, "Predicting gender from footfalls using a seismic sensor," *2017 9th International Conference on Communication Systems and Networks (COMSNETS)*, Bangalore, 2017, pp. 47-54. [Download Link]

Patents Granted

1. S. Kar, B. Mukhopadhyay, and **S. Anchal**. Diagnosis of subclinical mastitis in dairy animals. Granted: Indian Patent Number 357347.

Prototypes

1. Real-Time Footstep-based Person Identification and Imposter Detection System

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	i
ABSTRACT	iii
LIST OF TABLES	xiv
LIST OF FIGURES	xvii
ABBREVIATIONS	xviii
1 INTRODUCTION	1
1.1 Motivation	1
1.2 Main Contributions of the Thesis	3
1.3 Compliance with guidelines for ethical research of IIT Delhi	6
1.4 Organization of the thesis	8
1.5 Literature Review	11
1.5.1 Review of usage of footsteps as the biometric modality	11
1.5.2 The use of Seismic Sensors for footstep detection	13
1.5.3 Identification of persons using footsteps	14
1.5.4 Imposter Detection	19
1.5.5 Domain Adaptation in seismic sensor based applications	19
2 A Novel Method for Person Identification Using Footfalls Signals for Smart Home Applications	23
2.1 Introduction to person identification for smart homes	23
2.2 A System Architecture for footstep based Person Identification	24
2.2.1 Signal Acquisition	27
2.2.2 Event Extraction	27
2.2.3 Signal Compression and Decompression	29
2.3 Feature Engineering	33

2.4	Classification and Data storage	38
2.5	Results and Discussion	40
2.5.1	Selection of optimal number of footsteps/sample	42
2.5.2	Selection of best suitable classifiers for person identification	43
2.5.3	Selection of optimal sampling frequency	45
2.5.4	Selection of optimal number of training samples per class	46
2.5.5	Comparative analysis of the proposed person identification technique	48
2.5.6	Performance of the system in various surface types and sensor footprint distance	48
2.5.7	Performance of the proposed compression and de-compression technique	51
2.5.8	DS8BP works as a denoising filter	55
2.6	Hardware Implementation	58
2.7	Summary of this Chapter	60
3	Person Identification and Imposter Detection using Footfall generated Seismic Signal	61
3.1	Introduction to Imposter Detection	61
3.2	Person Identification and Imposter detection framework	62
3.2.1	USLEET: Unsupervised learning based event detection and extraction technique	63
3.2.2	Feature engineering	68
3.2.3	Person Identification	70
3.2.4	Detection of unregistered user (imposter)	70
3.3	Results and Discussion	73
3.3.1	Dataset details	73
3.3.2	Performance of USLEET	74
3.3.3	Performance of the proposed person identification technique	75
3.3.4	Performance of the proposed imposter detection technique	80
3.4	Chapter Summary	87
4	A Statistical Approach for Person verification for Smart Homes Applications	88
4.1	Introduction to person verification	88

4.2	System architecture for person verification	89
4.2.1	Signal Recording	89
4.2.2	Signal Preprocessing	91
4.2.3	Person Verification using GMM-UBM	92
4.3	Experimental Methodology	94
4.3.1	Experimental Setup and Evaluation Matrix	94
4.3.2	Experimental Results	96
4.4	Chapter Summary	97
5	Footstep-based Cross-Domain Person Identification using Semi-Supervised Domain Adaptation	99
5.1	Introduction to cross-domain person identification	99
5.2	Proposed Framework for Cross-Domain Person Identification	103
5.2.1	Problem Definitions and Notations	104
5.2.2	Brief Review of Sparse Filtering	105
5.2.3	Class Aware Semi-Supervised and Self-Supervised Domain Adaptation Method	107
5.3	Experiments and Results	112
5.3.1	Dataset Details and Collection Protocol	113
5.3.2	Details of the Implementation	114
5.3.3	Performance Comparison with the prior-art	115
5.3.4	Comparison with Existing Person Identification Method . .	121
5.3.5	Ablation Study	122
5.3.6	Qualitative Analysis via Visualization	128
5.4	Chapter Summary	129
6	FootsNet: A Convolutional Neural Network for Person Identification	130
6.1	Introduction to Transfer Learning for Person Identification	130
6.2	System Architecture of FootsNet for Person Identification	131
6.2.1	Signal Recording and Preprocessing	131
6.2.2	1D-CNN Model	133
6.2.3	Training Methodology	134
6.3	Experiments and Results	134
6.3.1	Performance Analysis	135

6.4	Chapter Summary	137
7	Conclusions and future work	139
7.1	Conclusion	139
7.2	Future Work	141
7.2.1	Deep learning-based solution for high precision imposter de- tection	141
7.2.2	Source-separation problem for detecting multiple persons .	142
7.2.3	Application of Semi-Supervised or Self-Supervised learning	142
7.2.4	Application of Domain Generalization techniques	143
	Bibliography	143
	List of Publications	156
	Brief Profile of the Author	157

LIST OF TABLES

1.1	Comparison among existing footstep based biometric system.	15
1.2	Synopsis of footstep-based methods with/without domain adaptation (DA)	20
2.1	Features extracted from a single footstep event	33
2.2	Features showing similarity among the footstep signals of a particular individual and dissimilarity among the footstep signals of different individuals.	36
2.3	Details of the footstep datasets.	40
2.4	Performance of different classifiers on the footstep dataset DS_M . . .	44
2.5	Confusion matrix of SVM-RBF when the footstep signals are sampled at 500 Hz.	45
2.6	Performance of person identification techniques using DS_M	47
2.7	Performance of the person identification system in different floor types.	49
2.8	Performance of the person identification system with the variation in the sensor footstep distance.	50
2.9	Performance of DS8BP in different floor types.	52
2.10	Transmission time of a single footstep event achieved by the compression techniques (Length of a footstep event = 2005 samples and transmission rate = 80 kbps)	53
2.11	Structure of the tables present in the <i>Edge Units</i> and the <i>Cloud</i>	59
2.12	Computational time of the processing steps of the proposed 3-layer architecture for a single footstep event.	59
3.1	Features used by USLEET for event detection.	65
3.2	Feature set used for person identification and imposter detection	69
3.3	Person identification with varying footsteps per sample (dataset used DS_{con}).	75
3.4	Confusion Matrix of the SVM-RBF for 2 footsteps per sample using USLEET.	78
3.5	Comparison of the proposed person identification technique with the existing person identification technique.	78
3.6	Performance of person identification on different floor types.	79

3.7	Details of the scenarios used for performance analysis of imposter detection.	79
3.8	Performance of SVDD for different imposter detection scenarios. . .	82
3.9	Performance of SVDD in imposter detection using footstep data recorded in carpet floor (dataset used DS_{car}).	83
3.10	Performance of SVDD in imposter detection using footstep data recorded in wooden floor (dataset used DS_{wood}).	84
3.11	Performance of SVDD in imposter detection using footstep data recorded in concrete tile floor (dataset used DS_{con}).	85
4.1	Performance of GMM-UBM, SVM, and CNN in person verification	96
4.2	Inference time of the techniques	97
5.1	Frequently used Notations and their Descriptions	105
5.2	Details of the datasets used in this work	114
5.3	Target classification accuracy(%) obtained from different domain adaptation methods on Floor-3-12 dataset.	117
5.4	Target classification accuracy(%) obtained from different domain adaptation methods on the Distance-3-10 dataset	118
5.5	Comparison of baselines with our proposed method. The Accuracy and F1 Scores are averaged over all cross-domain tasks	122
6.1	Description of the layers of the 1D-CNN model.	133
6.2	Performance of the FoolsNet with respect to number for footstep samples per class	135
6.3	Performance comparison of the FoolsNet with the existing techniques.	135

LIST OF FIGURES

1.1	Ethical clearance report issued from the Institute Ethics Committee(IEC) of Indian Institute of Technology Delhi(IEC-IITD	7
1.2	Flow chart of the thesis organisation	9
2.1	The 3-layer computing architecture for person identification using footstep generated structural vibrations	25
2.2	Structural vibrations corresponding to ten consecutive footsteps. Each black dot (●) represents a single footstep	27
2.3	Adaptive Threshold Event Extraction Technique	28
2.4	The Dictionary (D) used by DS8BP to compress the footstep events	29
2.5	Datagram representation of a single footstep	31
2.6	Time and frequency domain representation of footstep events from three different individuals (P1, P2, and P3)	34
2.7	Study of correlations among the frequency domain representations of footstep events of an individual	36
2.8	Distinctive features among the footstep events of P1 and P3	37
2.9	Accuracy of different classifiers obtained by increasing the number of footsteps/sample (f_s is 8 kHz)	42
2.10	Training and testing accuracies of SVM-RBF as a function of the size of the training dataset	45
2.11	Variation of F1 score, event detection time (EDT), and feature extraction time (FET) as a function of f_s	46
2.12	Learning curve of all the classifiers on footstep dataset DS_M	47
2.13	Comparison between DS8BP and DS16 regarding compression capability	53
2.14	Performance analysis of classifiers on recovered signals after being compressed by DS8BP and DS16	54
2.15	Comparative analysis of DS8BP with existing compression techniques	55
2.16	Denoising property of the DS8BP technique	56
2.17	Floor planning and hardware components for implementing person identification system	57
2.18	Flow charts of Algorithms running in EP , EP^{++} and $Cloud$	58

3.1	Overview of the proposed person identification and imposter detection technique	63
3.3	Illustration of the event extraction process using USLEET	66
3.4	Effect of rectangular and Gaussian window on the frequency content of the extracted footstep event	67
3.5	Time and frequency domain representation of footstep events recorded in concrete tile floor	69
3.6	Performance of the event detection/extraction techniques(dataset used DS_{ED})	74
3.7	Performance of SVM-RBF in person identification with USLEET, UREDT, and Adap-Th. (dataset used DS_{con})	76
3.8	Learning curve of SVM-RBF accompanied with USLEET/Adap-Th. for person identification	77
3.9	Performance of SVDD, OC-SVM and OC-CNN in different imposter detection scenarios (10 footsteps/sample)	80
3.10	ROC curves for imposter detection using one-class classifiers. AUC:-Area Under the Curve	86
4.1	Footstep based person verification system using GMM-UBM	90
4.2	Illustration of the event extraction process	91
4.3	HTER for the test set for different Gaussian mixture size	95
4.4	Performance of the GMM-UBM, CNN and SVM-RBF techniques when $r_{reg} = 6$ and $r_{nreg} = 5$	97
5.1	Time-domain representation of the footstep event collected in different underlying floors and at different human-to-sensor distances	101
5.2	Illustration of the concept of the footstep-based cross-domain person identification	103
5.3	Seismic Signal induced from the footsteps(represented by ●) on wooden floor	104
5.4	Structure of the Sparse Filtering	106
5.5	Proposed deep neural network architecture of Class Aware Semi-Supervised and Self-Supervised Domain Adaptation(CA-S4DA)	108
5.6	Average F1 Score of different domain adaptation methods obtained from two Domain Adaptation datasets	119
5.7	Performance comparison with respect to the existing person identification methods utilizing seismic sensor for a) Floor-3-12 and b) Distance-3-10 dataset	120

5.8	Effect of the number of labelled target footsteps in domain adaptation: a) Obtained for Cr→W cross-domain task in Floor-3-12 dataset and b) Obtained for D2→D3 cross-domain task in Distance-3-10 dataset .	123
5.9	Effect of the number of unlabelled target footsteps in domain adaptation: a) Obtained for Cr→W cross-domain task in Floor-3-12 dataset and b) Obtained for D2→D3 cross-domain task in Distance-3-10 dataset	125
5.10	Performance of domain adaptation technique with number of consecutive footstep events(N_e) consider in both source and target domains for a) Cr→W and b) D2→D3	127
5.11	t-SNE visualization of target features obtained for Cr→W domain adaptation task during the testing phase	128
6.1	System Architecture of the FoothNet	132
6.2	Performance with respect to different number of novel classes . . .	136
6.3	Feature visualization of novel classes using t-SNE	137

ABBREVIATIONS

IEC	Institute Ethics Committee
SA	Sensing Area
EP	Embedded Processor
ADC	Analogue to Digital Converter
SNR	Signal to Noise Ratio
URED T	Unsupervised Learning Real-Time Event Detection Technique
USLEET	Unsupervised Learning Event Extraction Technique
GMM	Gaussian Mixture Model
UBM	Universal Background Model
SVM	Support Vector Machine
RBF	Radial Basis Function
LSVM	Linear Support Vector Machine
ANN	Artificial Neural Network
LR	Logistic Regression
LDA	Linear Discriminant Analysis
OC-SVM	One-Class Support Vector Machine
SVDD	Support Vector Data Description
1C-Models	One Class Models
IoT	Internet of Things
ROC	Receiver Operation Characteristics
FRR	False Rejection Ratio
FAR	False Acceptance Ratio
HTER	Half Total Error Rate
CNN	Convolutional Neural Network
SF	Sparse Filter
TCA	Transfer Component Analysis
UDA	Unsupervised Domain Adaptation
SSDA	Semi-Supervised Domain Adaptation

MMD	Maximum Mean Discrepancy
DANN	Domain Adversarial Neural Network
FM	Feature Module
FC	Fully Connected Layer
FusL	Fusion Layer
BN	Batch Normalization
SGD	Stochastic Gradient Descent
DTL	Deep Transfer Learning
DADA	Deep Adversarial Domain Adaptation
MME	Minimax Entropy
FS-ADA	Few-Shot Adversarial Domain Adaptation
GAN	Generative Adversarial Network
MMD-PD	Maximum Mean Discrepancy - Parallel Data
SCA	Supervised Class Alignment
CA-S4DA	Class-Aware Semi-Supervised Self-Supervised Domain Adaptation
t-SNE	t-Stochastic Neighbourhood Embeddings