PERSON IDENTIFICATION THROUGH FOOTSTEP-BASED BIOMETRIC RECOGNITION

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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.

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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, पदचिन्ह 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। फ़ुटस्टेप 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। धोखेबाज़ का पता लगाने के लिए यथार्थवादी परिदृश्यों की नकल करने के लिए, मॉडलों को केवल पंजीकृत उपयोगकर्ताओं के फ़ुटस्टेप 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 धोखेबाज़ 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 दिया[4]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 है[4]तीन 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।

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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]

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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]

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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.

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Patent granted

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

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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

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ABBREVIATIONS

IEC	Institute Ethics Committee
SA	Sensing Area
EP	Embedded Processor
ADC	Analogue to Digital Converter
SNR	Signal to Noise Ratio
UREDT	Unsupervised Learning Real-Time Event Detection Technique
USLEET	Unsupervised Learning Event Extraction Technique
GMM	Gaussian Mixture Model
UBM	Universal Backgroud 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