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It is certified that the work contained in the thesis titled ***"Smart Sensing Based Approaches for Supporting the Independent Living of the Elderly"*** by ***Atul Chaudhary*** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all requirements of Comprehensive Examination, Candidacy, and SOTA for the award of Ph.D. Degree.

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I, ***Atul Chaudhary***, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of ***Dr. Hari Prabhat Gupta*** and ***Prof. K. K. Shukla*** from ***July 2017*** to ***November 2021*** at ***Department of Computer Science and Engineering***, Indian Institute of Technology (BHU) Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc.* reported in journals, books, magazines, reports, dissertations, theses, *etc.*, or available at websites and have not included them in this thesis and have not cited as my own work.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Dedicated to my family,

Mrs. Seema (Wife)

and

Ms. Khushi Choudhary (Daughter)

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(Atul Chaudhary)

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List of Symbols

Symbol	Description
l	Sliding window size
k	Number of sensors
n	Number of activities (including “Other”activity)
z	Number of events of sensor stream
$\mathcal{A} = \{a_1, a_2, ...a_n\}$	Set of activity labels/classes
$\mathcal{S} = \{s_1, s_2, ...s_k\}$	Set of sensors
$\mathbf{e} = \{e_1, e_2, ...e_z\}$	Sensor event stream
$e_i =< d_i, t_i, s_i, v_i >$	i^{th} event of sensor stream, where d_i, t_i, s_i, and v_i are date, time, sensorID, and sensor value, respectively
$\mathbf{W} = \{W_1, W_2, ...\}$	Sliding windows of raw sensor events
$W_i = \{e_i, e_{i+1}, ...e_{i+l-1}\}$	i^{th} sliding window
L_i	i^{th} location in a smart home
T_{th}	Time interval for episode segmentation
$\mathcal{M}'$	Set of motion sensors (excluding wide area sensors)
$M = ((L_1 L_2), ..., (L_{n-1}, L_n))$	Movements
$E = (L_1, L_2, ..., L_n)$	Episode
$\mathbf{E} = (E_1, E_2, ..., E_n)$	List of n episodes
$\mathbf{D}_i$	i^{th} dataset
$T = \{\mathcal{Y}, f_T(.)\}$	Task, where $\mathcal{Y}$ and $f_T(.)$ are label space and target prediction function, respectively
$D_s = \{x_s, y_s\}$	Source domain
$D_t = \{x_t, y_t\}$	Target domain

Abbreviations

Abbreviation	Description
ADL	Activities of Daily Living
ADLP	Activities of Daily Living Prediction
ADLR	Activities of Daily Living Recognition
CASAS	Center for Advanced Studies in Adaptive Systems
CEL	Cross-Entropy Loss
CL	Center Loss
CNN	Convolutional Neural Network
DCNN	Deep Convolutional Neural Network
DNN	Deep Neural Network
EDD	Early Dementia Detection
FL	Focal Loss
GRU	Gated Recurrent Unit
HCF	Hand-Crafted Feature
HLF	High-Level Feature
IMU	Inertial Measurement Unit
IR	InfraRed
LSTM	Long Short Term Memory
MAE	Mean Absolute Error
MLP	Multi-Layer Perceptron
OADR	Old-age dependency ratio
PIR	Passive InfraRed
PwD	People with Dementia
RNN	Recurrent Neural Network
SVM	Support Vector Machine
TNADLR	Transfer Network for Activities of Daily Living Recognition

Preface

The aging of the world population is becoming more and more serious. It has created an increasing need for new and innovative assistive technologies to improve older adults' lives while reducing the burden placed on the healthcare system and caregivers. Older adults are at significant risk of having multiple chronic diseases and associated functional impairment. For many older adults, these concerns are further compounded by the presence of cognitive impairment such as dementia. Dementia is considered to be one of the greatest challenges for health and social care in the 21st century. A significant challenge in dementia is achieving an accurate and timely diagnosis. If the patient can have proper medical treatment at an early stage, then the dementia growth can be delayed by months to years. Moreover, because of the ongoing novel coronavirus disease (COVID-19) pandemic, healthcare experts and doctors advised older adults to live in isolation since they have a high risk of contracting the virus. Individuals need to complete Activities of Daily Living (ADL) to function independently at home. ADL consists of necessary self-care activities such as eating, cooking, drinking, dressing, taking medication, and sleeping. Many older adults with mental illnesses and chronic diseases have difficulties in performing ADL tasks.

Meanwhile, older adults prefer to live in their own homes for as long as possible rather than move to aged care facilities. Consequently, smart homes have become an active research domain, especially in providing healthcare and assistive services. Smart homes employ various sensors, actuators, and computational elements to help the inhabitants in many possible situations and assist them with daily activities. They involve many technologies, including ADL recognition, future ADL prediction, early diagnosis of illness, and prompting system. Such technologies focus on augmenting current health care services to help older adults live a quality of independent life in their places and extend the time that an older adult can live self-sufficiently.

The existing literature considered different sensor modalities to gather human activities information for developing assistive technologies, including environmental sensors, wearable sensors, and video sensors. However, video sensors are not practical due to privacy issues, and the accuracy of wearable sensors relies upon the body attachment position. Next, most of the existing literature on ADL recognition considers class balanced data, while the real-life datasets are significantly imbalanced. Such imbalanced training data can result in a biased system optimized to favor the majority classes while failing to recognize the minority classes. In addition to these, prior works either use hand-crafted features or high-level features to recognize the ADL. Moreover, until now, research on ADL recognition has mostly centered around offline recognition. The unpredictability of future events and the requirement of dealing with the un-segmented activity streams make online ADL recognition very challenging.

In this thesis, we investigate different smart sensing based approaches for supporting the independent living of the elderly. We primarily focus on environmental or external sensors for unobtrusive monitoring such as infrared motion, magnetic door, light, or temperature sensors. These sensors are embedded in the environment or objects of daily living. Their non-intrusive characteristics make them suitable for assistive technologies where user acceptance and privacy are needed. The first contribution of this thesis is to detect dementia at an early stage using unobtrusive sensor data. As a solution, this work proposes an early dementia detection system using older adults' travel pattern classification. We use the environmental sensor signals for sensing the movements of older adults. The system segments the movements into travel episodes and classifies them using a recurrent neural network. The second contribution of this thesis is to predict the ADL older adults will perform ahead of time. We propose a multi-task activity prediction system that jointly predicts future activities' labels, locations, and starting times. In this work, the observed sequence of previous activities characterizes future activities. The next contribution of this thesis is to recognize ADL in real-time through supervised learning. This work proposes a system that unobtrusively recognizes ADL in real-time from streaming sensor data addressing the long-tailed class distribution problem. The proposed system effectively combines deep learned features with hand-crafted features to recognize ADL better. In the last contribution, we address the problem of recognizing ADL through transfer learning that can leverage labeled data from a different smart home. As a solution, this work proposes a transfer network for ADL recognition through unsupervised domain adaptation between smart homes with different spatial layouts and sensor deployment.