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Jorge Luis Reyes Ortiz

Smartphone-Based Human Activity Recognition

Doctoral Thesis accepted by
Universitat Politècnica de Catalunya, Spain and Università degli Studi di Genova, Italy

Springer

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... a mi familia, el motor de mi vida.

Supervisor's Foreword

It is a great pleasure to introduce the thesis work of Dr. Jorge Luis Reyes Ortiz, accepted for publication within Springer Theses and awarded with a prize for outstanding original work. In February 2011, Dr. Reyes Ortiz started his 3-year joint Ph.D. research program in Interactive and Cognitive Environments at the *Universitat Politècnica de Catalunya* in Spain and at the *Università degli Studi di Genova* in Italy.

This thesis is one of the first works addressing a topic of very high interest: the use of smartphones for the recognition of human activities. Smartphones are one the most popular devices users interact with everyday while performing their usual activities. This aspect combined with their sensing, computing, and communication capabilities make them a fundamental tool for pervasively acquiring and extracting user information. Moreover, there is an increasing interest in the development of systems that exploit this information to promote the improvement of people's quality of life, including that of individuals with any type of limitation and lack of general well-being.

This work presents a series of contributions regarding the development of Human Activity Recognition (HAR) systems with smartphones. In the first place, Dr. Reyes Ortiz proposes a fully operational system that recognizes in real-time six physical activities. For achieving this, various research areas are covered, which range from signal processing and feature selection of inertial data, to Machine Learning approaches for classification.

Two smartphone sensors (the accelerometer and the gyroscope) are employed for collecting inertial data. Their raw signals are the system input and they are conditioned through filtering in order to reduce noise and allow the extraction of informative activity features. This work also emphasizes the study of the Support Vector Machine (SVM), which is one of the state-of-the-art supervised Machine Learning algorithms for classification. The standard SVM is reformulated in order to find the best tradeoff between recognition performance, computational costs, and energy requirements. These aspects are essential in battery-operated devices such as smartphones. In particular, two multiclass SVMs for activity classification are proposed: one linear algorithm that allows control over dimensionality reduction and system accuracy; and also a nonlinear hardware-friendly algorithm that only uses fixed-point arithmetic in the prediction phase and enables a model complexity reduction while maintaining the system performance. The effects of postural transitions that occur between activities and affect the classification performance are also studied in this research.

The efficiency of the proposed system is verified through extensive experimentation over a HAR dataset, which have been generated and made publicly available. It is composed of inertial data collected from a group of 30 participants, who performed a set of common daily activities while carrying a smartphone as a wearable device.

The results achieved in this research show that it is possible to perform HAR in real-time with a precision near 97 % with smartphones. In this way, the proposed methodology can be employed in higher-level applications that require HAR such as ambulatory monitoring of the disabled and the elderly during periods above five days without the need for a battery recharge. Moreover, the proposed algorithms can be adapted to other commercial wearable devices recently introduced in the market (e.g., smart watches and glasses). This will open up new opportunities for developing practical and innovative HAR applications.

Genova, October 2014 Prof. Davide Anguita

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According to ICE regulations, the Italian Ph.D. title has also been awarded by the Università degli Studi di Genova.

Contents

Mathematical Symbols and Notations

Table 1 Most commonly used mathematical symbols in this thesis

Symbol	Description
$\boldsymbol{x} \in \mathbb{R}^d$	Input sample of d dimensions
$X \in \mathbb{R}^{n \times d}$	Set of n vector samples of dimension d
$x_{i,j}$	j-th feature of the i-th sample
$y \in \{-1, 1\}$	Output target in binary classification problems
$y \in \{1, \cdots, m\}$	Output target in m-class problems with $m \in \mathbb{N}_1 > 2$
$\boldsymbol{y} \in \mathbb{Z}^n$	Vector of n output targets y_i
$f_c(\boldsymbol{x}) \in \mathbb{R}$	SVM output of a sample for class c
$\boldsymbol{f}(\boldsymbol{x}) \in \mathbb{R}^m$	SVM output vector for a m-class problem
$p_c(\boldsymbol{x}) \in [0, 1] \subset \mathbb{R}$	SVM probability output
$\boldsymbol{p}(\boldsymbol{x}) \in \mathbb{R}^m$	SVM probability output vector
$c^* \in \{1, \cdots, m\}$	SVM predicted class
$\boldsymbol{a}(t) \in \mathbb{R}^3$	Time-domain triaxial body acceleration signal
$\boldsymbol{\omega}(t) \in \mathbb{R}^3$	Time-domain triaxial angular velocity signal
$\boldsymbol{g}(t) \in \mathbb{R}^3$	Time-domain gravity signal
T	Window sampling period in seconds
N	Number of samples in an activity window
k	Number of bits for the fixed-point number representation

Table 2 Notation of the presented SVM Machine Learning algorithms

SVM Algorithm				
Name	**Binary**	**Multiclass**	**Norm**	$K(\boldsymbol{x}_i, \boldsymbol{x}_j)$
Linear				
L1 Manhattan	L1-SVM	MC-L1-SVM	$\|\boldsymbol{w}\|_1$	$\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{x}$
L2 Euclidean	L2-SVM	MC-L2-SVM	$\|\boldsymbol{w}\|_2$	$\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{x}$
L1-L2	L1-L2-SVM	MC-L1-L2-SVM	$\|\boldsymbol{w}\|_1, \|\boldsymbol{w}\|_2$	$\boldsymbol{x}^{\boldsymbol{T}}\boldsymbol{x}$
Non-Linear				
Gaussian	GK-SVM	MC-HF-SVM	$\|\boldsymbol{w}\|_2$	$e^{-\gamma\|\boldsymbol{x}_i - \boldsymbol{x}_j\|_2^2}$
Laplacian	LK-SVM	MC-LK-SVM	$\|\boldsymbol{w}\|_2$	$e^{-\gamma\|\boldsymbol{x}_i - \boldsymbol{x}_j\|_1}$
Hardware-Friendly	HF-SVM	MC-HF-SVM	$\|\boldsymbol{w}\|_2$	$2^{-\gamma\|\boldsymbol{x}_i - \boldsymbol{x}_j\|_1}$

Table 3 Notation of the Proposed HAR systems

HAR System						
Name	**Notation**	**ML Algorithm**	**Activities**	**Dataset**	**Online**	**Chap.**
Hardware Friendly	HF-HAR	MC-HF-SVM	6BAs	$\mathcal{D}_1$	–	5
Linear	L-HAR	MC-L1-SVM MC-L2-SVM MC-L1-L2-SVM	6BAs	$\mathcal{D}_2$, $\mathcal{D}_{2T}$	✓	6
Postural Transition Aware	PTA-HAR	MC-L1-SVM	6BAs, 6BAs + PTs	$\mathcal{D}_{3T}$	✓	7

Abbreviations

AA	Ambulation Activity
AAL	Ambient-Assisted Living
ADL	Activities of Daily Living
ADT	Android Development Tools
AmI	Ambient Intelligence
ANN	Artificial Neural Networks
API	Application Programming Interface
BA	Basic Activity
BDM	Bayesian Decision Making
BSN	Body Sensor Network
CA	Complex Activity
CCQP	Convex Constrained Quadratic Programming
cHMM	Continuous Emissions HMM
CPU	Central Processing Unit
DFT	Discrete Fourier Transform
DT	Decision Tree
DTW	Dynamic Time Warping
EDGE	Enhanced Data rates for GSM Evolution
ESANN	European Symposium on Artificial Neural Networks
EX-SMO	Extended SMO
FFP	Feed-Forward Phase
FFT	Fast Fourier Transform
FN	False Negatives
FP	False Positives
GDA	Gaussian Discriminant Analysis
GK-SVM	SVM with Gaussian Kernel
GMM	Gaussian Mixture Models
GMR	Gaussian Mixture Regression
GPRS	General Packet Radio Service
GPS	Global Positioning System
GUI	Graphical User Interface

HAR	Human Activity Recognition
HARApp	Human Activity Recognition Application
HF-HAR	Hardware-Friendly Human Activity Recognition (HAR) System
HF-SVM	Hardware-Friendly SVM
HMM	Hidden Markov Models
KCV	*k*-Fold Cross Validation
KKT	Karush-Kuhn-Tucker
k-NN	k-Nearest Neighbors
L1-L2-SVM	L1-L2-Norm SVM
L1-SVM	L1-Norm SVM
L2-SVM	L2-Norm SVM
LD	Lying-down
LDA	Linear Discriminant Analysis
L-HAR	Linear HAR System
LiSi	Lie-to-sit
LiSt	Lie-to-stand
LK-SVM	SVM with Laplacian Kernel
LR	Logistic Regression
LSM	Least Squares Method
LUT	Look-Up-Table
LVQ	Learning Vector Quantization
MAP	Maximum A Posteriori Probability
MC-GK-SVM	MultiClass GK-SVM
MC-HF-SVM	MultiClass HF-SVM
MC-L1-L2-SVM	MultiClass L1-L2-SVM
MC-L1-SVM	MultiClass L1-SVM
MC-L2-SVM	MultiClass L2-SVM
MC-LK-SVM	Multiclass LK-SVM
MEMS	Microelectromechanical Systems
ML	Machine Learning
MLP	Multilayer Perceptron
MMS	Multimedia Messaging Service
NB	Naive Bayes
NDK	Native Development Kit
NFC	Near Field Communication
OS	Operating System
OVA	One-vs-all
OVO	One-vs-one
PCA	Principal Component Analysis
PD	Parkinson's disease
PDA	Personal Digital Assistant
PerComp	Pervasive Computing
PET	Positron Emission Tomography
PT	Postural Transition

PTA-6A	PTA-HAR with 6 Basic Activities (BAs)
PTA-7A	PTA-HAR with 6 BAs + 6 Postural Transitions (PTs)
PTA-HAR	Postural Transition Aware HAR System
QoL	Quality of Life
QP	Quadratic Programming
RBF	Radial Basis Function
RF	Random Forest
RL	Reinforcement Learning
SDK	Software Development Kit
SGSII	Samsung Galaxy SII
SI	Sitting
SiLi	Sit-to-lie
SIM	Subscriber Identity Module
SiSt	Sit-to-stand
SLT	Statistical Learning Theory
SMA	Signal Magnitude Area
SMLP	Simplex Method for Linear Programming
SMO	Sequential Minimal Optimization
SMS	Short Message Service
SP	Static Posture
SRM	Structural Risk Minimization
ST	Standing
STD	Standard Deviation
StLi	Stand-to-lie
StSi	Stand-to-sit
SVM	Support Vector Machine
TN	True Negatives
TP	True Positives
UA	Unknown-activity
UbiComp	Ubiquitous Computing
USB	Universal Serial Bus
WD	Walking-downstairs
WEKA	Waikato Environment for Knowledge Analysis
WK	Walking
WU	Walking-upstairs

Author Biography

Jorge Luis Reyes Ortiz was born in Barranquilla, Colombia in 1980. He received his B.Sc. in Electronic Engineering in 2003 at the Universidad Pontificia Bolivariana and his M.Sc. in Artificial Intelligence in 2008 at the University of Edinburgh. His studies were followed by a joint Ph.D. degree in Interactive and Cognitive Environments in 2014 at the University of Genoa and Universitat Politècnica de Catalunya, with focus on human activity recognition using smartphones. He is currently a research assistant at the University of Genoa and his work targets scalable Machine Learning approaches for Big Data Analytics.

He has also worked in the industry: first in the hygiene products sector where he managed the electronic maintenance department of the production lines at Familia Sancela del Pacfico Ltda. in 2003. Then he worked as a software developer for the real-time analysis and visualization of sporting events at Spinsight Ltd. in 2008.