Neural Networks 102 (2018) 107–119

Contents lists available at ScienceDirect

Neural Networks

journal homepage: www.elsevier.com/locate/neunet

Adaptive Bayesian inference system for recognition of walking activities and prediction of gait events using wearable sensors

Uriel Martinez-Hernandez *, Abbas A. Dehghani-Sanij

Institute of Design, Robotics and Optimisation (iDRO), The School of Mechanical Engineering at the University of Leeds, Leeds, LS2 9JT, UK

ARTICLE INFO

Article history:
Received 19 April 2017
Received in revised form 23 January 2018
Accepted 26 February 2018
Available online 9 March 2018

Keywords:
Intent recognition
High-level control
Bayesian inference
Action–perception architectures
Wearable sensors

ABSTRACT

In this paper, a novel approach for recognition of walking activities and gait events with wearable sensors is presented. This approach, called adaptive Bayesian inference system (BasIS), uses a probabilistic formulation with a sequential analysis method, for recognition of walking activities performed by participants. Recognition of gait events, needed to identify the state of the human body during the walking activity, is also provided by the proposed method. In addition, the BasIS system includes an adaptive action–perception method for the prediction of gait events. The adaptive approach uses the knowledge gained from decisions made over time by the inference system. The action–perception method allows the BasIS system to autonomously adapt its performance, based on the evaluation of its own predictions and decisions made over time. The proposed approach is implemented in a layered architecture and validated with the recognition of three walking activities: level-ground, ramp ascent and ramp descent. The validation process employs real data from three inertial measurements units attached to the thigh, shanks and foot of participants while performing walking activities. The experiments show that mean decision times of 240 ms and 40 ms are needed to achieve mean accuracies of 99.87% and 99.82% for recognition of walking activities and gait events, respectively. The validation experiments also show that the performance, in accuracy and speed, is not significantly affected when noise is added to sensor measurements. These results show that the proposed adaptive recognition system is accurate, fast and robust to sensor noise, but also capable to adapt its own performance over time. Overall, the adaptive BasIS system demonstrates to be a robust and suitable computational approach for the intelligent recognition of activities of daily living using wearable sensors.

1. Introduction

Recognition of human activities has played an important role for applications in healthcare, surveillance, human–computer interaction and teleoperation (Aggarwal & Ryoo, 2011; McColl, Jiang, & Nejat, 2017). In healthcare, recognition of activities of daily living (ADLs) is a key process to develop intelligent robots that understand human motion and provide reliable assistance (Brose et al., 2010; Erden & Billard, 2016). Particularly, activities that involve mobility such as walking in level-ground, ramps and stairs are essential for independence of living, transporting the human body safely and efficiently across terrains (Kirtley, 2006). Even though walking activities are normally taken as granted, they require coordinated movements difficult to be performed by elderly people or those who have suffered a physical injury (Winter, 1991).

Recent advances in sensor technology have enabled the development of small size and low cost wearable devices for applications that require physiological, biomechanical and motion data, e.g., electromyography (EMG) and inertial measurement units (IMUs) (Martinez-Hernandez, Boorman, & Prescott, 2017; Patel, Park, Bonato, Chan, & Rodgers, 2012; Zhang et al., 2015). Despite this progress, the design of reliable, fast and accurate computational methods that exploit the benefits offered by wearable sensors for recognition of human walking activities still remain a challenge.

In this work, a Bayesian inference system (BasIS) for recognition of walking activities using wearable sensors is presented. The BasIS system uses a probabilistic formulation that, together with a sequential analysis method, iteratively accumulates sensor data to improve the recognition of walking activities. This approach is inspired by the *competing accumulators* model for decision-making proposed by neuroscientists (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Smith & Ratcliff, 2004), and applied to robotics in tasks such as perception, learning, exploration and interaction (Lepora et al., 2015; Martinez-Hernandez, Dodd, Evans, Prescott, & Lepora, 2017; Petit, et al., 2013). In addition, the BasIS system is capable to recognise the gait events that compose the walking activity. These functionalities are essential to recognise

* Corresponding author.
E-mail address: u.martinez@leeds.ac.uk (U. Martinez-Hernandez).

https://doi.org/10.1016/j.neunet.2018.02.017
0893-6080/

the activity performed by a subject, but also to know the state of the human body during the walking cycle.

An adaptive action–perception method is presented to extend the BasIS system to improve the recognition accuracy and speed. This method uses a weighted combination of information sources, which is inspired by the way in that humans make decisions. Studies have shown that human decision-making combines prior knowledge and current expectations, weighted according to the accuracy of decisions made and reliability of information sources (Hanks, Mazurek, Kiani, Hopp, & Shadlen, 2011; Hansen, Hillenbrand, & Ungerleider, 2015). Thus, the adaptive BasIS system performs a weighted combination of (1) prior knowledge and (2) predicted information from the observation of decisions made over time. The proposed combination of information sources initialises the recognition process with a certain amount of knowledge, which is adapted over time to make the BasIS system reliable to changes observed from sensor inputs.

A layered architecture is developed to validate the adaptive BasIS system for the recognition of walking activities (level-ground walking, ramp ascent and descent) and gait events. The validation process uses real data collected from participants wearing IMU sensors attached to their lower limbs. Results show that the adaptive BasIS system is able to recognise walking activities and gait events with high accuracy and speed. In addition, significant improvement, in accuracy and speed, is observed using the prediction and weighted combination of information methods offered by the adaptive BasIS system. These results demonstrate the benefits of probabilistic methods for recognition of ADLs, but also show that the intelligent use of knowledge, gained over time, has the potential to improve the performance of autonomous inference systems.

Overall, the proposed probabilistic approach, together with wearable sensors, has shown to be a suitable high-level method for the development of intelligent and adaptable systems capable to recognise activities of daily living.

The remainder of this article is organised as follows: the literature review is described in Section 2. The method for recognition and prediction of walking activities and gait events is presented in Section 3. Experiments and validation of the proposed method are shown in Section 4. The discussion and conclusion of this research are presented in Sections 5 and 6, respectively.

2. Related work

A heuristic approach, with predefined rules and electromyography (EMG) signals from six muscles of participants, was used to recognise level-ground walking, ramp ascent and descent activities (Peeraer, Aeyels, & Van der Perre, 1990). Ground reaction force, hip and knee joint angles were used, together with a predefined set of rules and Finite State Machine (FSM), to identify sitting, standing and level-ground walking (Kawamoto & Sankai, 2002). These hard-coded methods are able to recognise ADLs, however, they do not take into account the uncertainty from sensor measurements, making these methods susceptible to fail for slight changes in the environment (Thrun, Burgard, & Fox, 2005).

Machine learning algorithm have played a key role in different disciplines, and it has not been the exception for the development of intent recognition methods. Linear Discriminant Analysis (LDA) and Artificial Neural Networks (ANN) have been widely used to identify ADLs with EMGs (Huang, Kuiken, & Lipschutz, 2009), time-domain and frequency domain features (Hargrove, Simon, Lipschutz, Finucane, & Kuiken, 2013). These works achieved accuracies from 80.0% to 94.1% for recognition of level-ground walking, stair ascent/descent and standing with a sampling window of 150 ms. A combination of ANN and heuristic methods identified walking, running, stair ascent and descent activities with accuracies ranging from 88.8% to 99% (Khan, Lee, & Kim, 2008; Staudenmayer, Pober, Crouter, Bassett, & Freedson, 2009). A drawback of these methods is the need for a large number of sensors, which makes the calibration, synchronisation and data collection complicated processes that impact on the computational cost and speed. An adaptive algorithm, based on decision trees and four sensors attached to the human body, was implemented for recognition of walking, standing and sitting with an accuracy of 99.0% (Rezaie & Ghassemian, 2017). Information from hip angle and pressure sensors was used with Fuzzy Logic (FL) methods for recognition of walking and stair ascent/descent, achieving an accuracy from 99.67% to 99.87% (Yuan, Parri, Yan, Wang, Munih, Vitiello et al., 2015; Yuan, Parri, Yan, Wang, Munih, Wang et al., 2015). High accurate identification of ADLs was achieved using a combination of FL and ANN methods with EMG signals (Chan, Yang, Lam, Zhang, & Parker, 2000; Hussein & Granat, 2002; Martinez-Hernandez, Rubio-Solis, Panoutsos, & Dehghani-Sanij, 2017). Neuromuscular-mechanical signals with Support Vector Machines (SVM), and fixed sampling window of 150 ms, were able to identify walking activities and gait phases (stance and swing) with accuracies of 97.0% and 99.0%, respectively (Huang et al., 2011). Multiple human activities were recognised with accuracies between 77.3% and 99.0% using SVMs with EMG and vision sensors. A drawback of this approach was the limitation to indoor applications (Gaglio, Re, & Morana, 2015). SVM and k-nearest neighbour (kNN) algorithms, together with 9 accelerometers distributed from the torso to the ankle, achieved an accuracy of 97.6% for the recognition of ADLs (Fullerton, Heller, & Munoz-Organero, 2017). Despite the high accuracy achieved by ANN and SVM methods, they produce black box models, which do not provide any measure of confidence or uncertainty of the decisions and actions made.

Probabilistic methods offer well-defined mathematical models for perception and learning, but also to handle sensor limitations and noise (Choi & Kim, 2015; Martinez-Hernandez, Dodd, & Prescott, 2017; Thrun et al., 2005). Bayesian formulations have demonstrated to be reliable for perception and control in robotics while dealing with uncertainty from sensors and the environment (Ferreira, Lobo, Bessiere, Castelo-Branco, & Dias, 2013; Martinez-Hernandez, Dodd, Evans et al., 2017; Martinez-Hernandez, Rubio-Solis, & Prescott, 2016). Gaussian Mixture Models (GMM) achieved a high accuracy of 100% with a decision time of 100 ms for identification of three locomotion activities (Varol, Sup, & Goldfarb, 2010). Walking activities on different terrains were successfully recognised using a Naïve Bayesian classifier trained with signals from IMU sensors (Farrell, 2013). Mechanical and EMG sensors have been used to train Dynamic Bayesian Networks (DBNs) for recognition of level walking, ramps and stairs, achieving recognition accuracies between 86.0% and 99.87% (Martinez-Hernandez, Mahmood, & Dehghani-Sanij, 2018; Young, Simon, Fey, & Hargrove, 2013; Young, Simon, & Hargrove, 2013). History information was employed, together with DBNs, to recognise walking activities and gait phases (stance and swing) with accuracies of 98.0% and 95.25%, respectively (Young, Simon, Fey, & Hargrove, 2014). This work was limited by the predefined and fixed amount of history or prior data for each new decision process. Even though the high accuracy achieved by the works previously described, they do not provide information about recognition of gait events. The recognition of walking activities, gait periods and events is crucial to develop systems capable to improve their decisions made over time. It has been shown that humans combine multiple source of information in decision-making processes, in order to make accurate decisions and actions (Körding & Wolpert, 2006). This combination of information has also been studied with humans and robots with multiple applications (Hansen et al., 2015; Martinez-Hernandez, Dodd, Evans et al., 2017). These works showed that