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Human gait recognition via deterministic learning☆

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ABSTRACT

Recognition of temporal/dynamical patterns is among the most difficult pattern recognition tasks. Human gait recognition is a typical difficulty in the area of dynamical pattern recognition. It classifies and identifies individuals by their time-varying gait signature data. Recently, a new dynamical pattern recognition method based on deterministic learning theory was presented, in which a time-varying dynamical pattern can be effectively represented in a time-invariant manner and can be rapidly recognized. In this paper, we present a new model-based approach for human gait recognition via the aforementioned method, specifically for recognizing people by gait. The approach consists of two phases: a training (learning) phase and a test (recognition) phase. In the training phase, side silhouette lower limb joint angles and angular velocities are selected as gait features. A five-link biped model for human gait locomotion is employed to demonstrate that functions containing joint angle and angular velocity state vectors characterize the gait system dynamics. Due to the quasi-periodic and symmetrical characteristics of human gait, the gait system dynamics can be simplified to be described by functions of joint angles and angular velocities of one side of the human body, thus the feature dimension is effectively reduced. Locally-accurate identification of the gait system dynamics is achieved by using radial basis function (RBF) neural networks (NNs) through deterministic learning. The obtained knowledge of the approximated gait system dynamics is stored in constant RBF networks. A gait signature is then derived from the extracted gait system dynamics along the phase portrait of joint angles versus angular velocities. A bank of estimators is constructed using constant RBF networks to represent the training gait patterns. In the test phase, by comparing the set of estimators with the test gait pattern, a set of recognition errors are generated, and the average L_1 norms of the errors are taken as the similarity measure between the dynamics of the training gait patterns and the dynamics of the test gait pattern. Therefore, the test gait pattern similar to one of the training gait patterns can be rapidly recognized according to the smallest error principle. Finally, experiments are carried out on the NLPR and UCSD gait databases to demonstrate the effectiveness of the proposed approach.

1. Introduction

Recognizing people by gait is a subfield of biometrics and is gaining increasing attention (Han & Bhanu, 2006; Huang & Boulgouris, 2008; Huang, Harris, & Nixon, 1999; Lee & Grimson, 2002; Murase & Sakai, 1996; Yoo & Nixon, 2011; Zhang, Vogler, & Metaxas, 2007). Gait offers the potential for vision-based recognition at a distance and is difficult to conceal or imitate the motion of an individual's walking (Winter, 1990).

Normal human walking may be defined as a method of locomotion which is a periodic or periodic-like process. Gait describes the manner or the style of walking and is a complex form of human locomotion while moving around in an orderly and stable manner (Yam, Nixon, & Carter, 2004). Motion trajectories, such as joint angles and vertical displacement trajectories, are the most widely used features in gait analysis (Lakany, 2008). Gait recognition approaches can be broadly divided into two categories: silhouette-based (or appearance-based) ones (Collins, Gross, & Shi, 2002; Kim, Kim, & Paik, 2010; Lam, Cheung, & Liu, 2011; Murase & Sakai, 1996; Wang, Ning, Hu, & Tan, 2003) and model-based ones (Huang & Boulgouris, 2009; Phillips, Sarkar, Robledo, Grother, & Bowyer, 2002; Tafazzoli & Safabakhsh, 2010; Wagg & Nixon, 2004; Yam & Nixon, 2009; Yoo, Nixon, & Harris, 2002). The silhouette-based approaches usually use a sequence of holistic binary silhouettes which are extracted from a video using segmentation techniques. They require good quality silhouette images to work

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with. The main advantages of these approaches are their simplicity and speed. However, silhouette dynamics is only indirectly linked to gait dynamics. It is difficult to infer the importance of different gait components from silhouette dynamics (Wagg & Nixon, 2004).

In model-based approaches, static or dynamic information is gathered from moving human bodies, such as joints or limbs. The information is then used to form a model with an underlying mathematical construct. This model represents the discriminatory gait characteristics. The model-based recognition system normally consists of gait capture, a static or dynamic feature extraction scheme, a gait signature and a classifier. Cunado, Nixon, and Carter (2003) modeled the thigh as a pendulum and extracted a hip joint trajectory from image sequences, then used the Fourier series to extract the leg's angular movements. A frequency-based gait signature was derived directly from the whole image sequence for recognition. Yam et al. (2004) extended the approach to describe the hip, thigh and knee angular motion of both walking and running gaits by an empirical motion model, then by an analytical model motivated by coupled pendulum motion. Phase-weighted Fourier description gait signatures were then derived from the extracted movements. Zhang et al. (2007) proposed a 2D model-based approach in which gait features were extracted by fitting a five-link biped human locomotion model to extract the joint position trajectories. The recognition step was performed using Hidden Markov Models based on the frequency components of these joint trajectories. Tafazzoli and Safabakhsh (2010) investigated the potential discriminatory capability of the gait signature obtained from different parts of the human body such as legs and arms. The subject was modeled based on anatomical proportions and recognition was carried out throughout the k-nearest neighbor classifier and Fourier components of the joint angles.

Recognition of temporal/dynamical patterns is among the most difficult pattern recognition tasks (Hong & Huang, 2002). Human gait recognition is a typical difficulty in the area of dynamical pattern recognition. One of the most difficult problems in dynamical pattern recognition is how to appropriately represent the time-varying patterns. Another important problem currently studied in this area is how to define the similarity between two dynamical patterns. Wang (2003) indicated that the methods for temporal pattern processing should be different from those for static pattern processing since the information of temporal patterns is embedded in time (thus inherently dynamic), not simultaneously available. In Wang and Hill (2007), a different framework was proposed for representation, similarity definition and rapid recognition of dynamical patterns. A time-varying dynamical pattern could be effectively represented in a time-invariant and spatially distributed manner. A similarity definition for dynamical patterns was given based on system dynamics. A mechanism for rapid recognition of dynamical patterns was presented by which a test dynamical pattern is recognized as similar to a training dynamical pattern if state synchronization is achieved according to a kind of internal and dynamical matching on system dynamics. Problems similar to those mentioned in the dynamical pattern recognition also exist in the process of human gait recognition, which can be solved by referring to the method mentioned in Wang and Hill (2007).

In this paper, we present a new model-based approach for human gait recognition via deterministic learning theory. The approach consists of two phases: a training (learning) phase and a test (recognition) phase. In the training phase, side silhouette lower limb joint angles and angular velocities are selected as gait features. A five-link biped model for human gait locomotion is employed to demonstrate that functions containing joint angle and angular velocity state vectors characterize the gait system dynamics. Due to the quasi-periodic and symmetrical characteristics of human gait, the gait system dynamics can be simplified to be described by functions of joint angles and angular velocities of one side of the human body, thus the feature dimension is effectively reduced. Since only joint angles are measurable from image sequences, a high-gain observer is used to estimate joint angular velocities. Locally-accurate identification of the gait system dynamics is achieved by using radial basis function (RBF) neural networks (NNs) through deterministic learning. The obtained knowledge of the approximated gait system dynamics is stored in constant RBF networks. Hence, time-varying gait dynamical patterns can be effectively represented by the locally accurate NN approximations of system dynamics, and this representation is time-invariant. These constant RBF networks trained via deterministic learning naturally have a certain ability of generalization (Wang & Hill, 2009), since whenever the trajectory of a test gait pattern lies within the local region of one training gait patterns, the corresponding RBF network will provide accurate approximation to the previously learned gait system dynamics. A gait signature is then derived from the extracted gait system dynamics along the phase portrait of joint angles versus angular velocities. A bank of estimators is constructed using the constant RBF networks to represent the training gait patterns and previously learned gait system dynamics is embedded in the estimators.

In the test phase, by comparing the set of estimators with the test gait pattern, a set of recognition errors are generated, and the average L_1 norms of the errors are taken as the similarity measure between the dynamics of the training gait patterns and the dynamics of the test gait pattern. Therefore, a test gait pattern similar to one of the training gait patterns can be rapidly recognized according to the smallest error principle. Compared with the existing gait recognition approaches, ours can learn the internal dynamics of human locomotion systems and apply the learned knowledge to the human gait recognition.

The rest of the paper is organized as follows. Section 2 introduces some preliminaries and the biped model of human gait locomotion. In Section 3, the joint angles and angular velocities are selected as gait features. Identification of human gait locomotion is achieved and a gait signature is derived from the extracted gait system dynamics. A recognition mechanism of human gait locomotion is presented. The experiments of gait recognition are given in Section 4 to demonstrate the effectiveness of our approach. Section 5 contains the conclusions.

2. Preliminaries

2.1. Deterministic learning theory

Recently, a deterministic learning theory was proposed for identification of nonlinear dynamical systems undergoing periodic or recurrent motions (Wang & Hill, 2007, 2009). It is shown that, by using localized RBF networks, almost any periodic or recurrent trajectory can lead to the satisfaction of a partial persistence of excitation (PE) condition. This partial PE condition leads to exponential stability of a class of linear time-varying adaptive systems. Consequently, accurate NN approximation of the system dynamics is achieved in a local region along the periodic or recurrent system trajectory. Further, by using the locally-accurate NN approximation of system dynamics, rapid recognition of a test dynamical pattern from a set of training dynamical patterns can be achieved (Wang & Hill, 2007).

The RBF networks can be described by $f_{nn}(Z) = \sum_{i=1}^{N} w_i s_i(Z) = W^T S(Z)$, where $Z \in \Omega_Z \subset R^p$ is the input vector, $W = [w_1, \ldots, w_N]^T \in R^N$ is the weight vector, N is the NN node number, and $S(Z) = [s_1(\|Z - \mu_1\|), \ldots, s_N(\|Z - \mu_N\|)]^T$ is the regressor vector, with $s_i(\|Z - \mu_i\|) = \exp[\frac{-(Z-\mu_i)^T(Z-\mu_i)}{\eta_i^2}]$, $i = 1, \ldots, N$ being a