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Human gait symmetry assessment using a depth camera and mirrors

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ABSTRACT

It is proposed in this paper a reliable approach for human gait symmetry assessment using a Time-of-Flight (ToF) depth camera and two mirrors. The setup formed from these devices provides a sequence of 3D point clouds that is the input of our system. A cylindrical histogram is estimated for describing the posture in each point cloud. The sequence of such histograms is then separated into two sequences of sub-histograms representing two half-bodies. A cross-correlation technique is finally applied to provide values describing gait symmetry indices. The evaluation was performed on 9 different gait types to demonstrate the ability of our approach in assessing gait symmetry. A comparison between our system and related methods, that employ different input data types, is also provided.

1. Introduction

The problem of assessing human gait has received a great attention in the literature since gait analysis is a key component of health diagnosis. Marker-based and multi-camera systems are widely employed to deal with this problem. Collections of wearable devices (e.g. inertial systems using accelerometer [1,2], gyroscope [3,4], and/or magnetometer [5,6]) are also considered to provide information about preselected body parts. However, such systems are less accessible due to their cost, size, need for accurate sensors/markers placement on the body and/or the necessity of trained staff to operate them. To alleviate these issues, we focus on a system of gait analysis which employs only one depth sensor. The principle is similar to a multi-camera system, but the collection of cameras are replaced by one depth sensor and mirrors. Each mirror in our setup plays the role of a camera which captures the scene at a different viewpoint. Since we use only one camera, the task of synchronization when working with multi-camera systems can thus be avoided, and the cost and complexity of devices are reduced. Our approach is especially appropriate for non-hospital settings (e.g. small clinics) and may complement more precise instruments (motion capture or inertial systems). Our system could enable clinicians to perform more frequent screening or follow-up of patient prior to more sophisticate tests involving gold standard systems in a specialized gait analysis lab or hospital when necessary.

In order to simplify the setup, recent vision-based studies used a color or depth camera to perform gait analysis. The input of such systems is thus either the subject's silhouette or depth map. Many gait signatures have been proposed based on the former input type such as Gait Energy Image (GEI) [7], Motion History Image (MHI) [8], or Active Energy Image (AEI) [9]. Typically they are computed based on a side view camera and are usually applied on the problem of human identification. In order to deal with pathological gaits, the input sequence of silhouettes needs more elaborate processing. In the work [10], the input sequence of silhouettes was separated into consecutive sub-sequences corresponding to gait cycles. The feature extraction was applied on each individual silhouette and the gait assessment was performed based on a combination of such features in each sub-sequence. Instead of capturing a side view of the subject, the authors in Refs. [11,12] put the camera in front of a walking person and tried to detect unusual movement. The balance of the subject was encoded based on a sequence of lattices applied on the captured silhouettes. A feature vector was then estimated for each lattice according to a predefined set of points, and the characteristic representing the whole motion was formed by concatenating such vectors. This step of concatenation is to incorporate the temporal context into the classification with a Support Vector Machine (SVM). A common limitation of such silhouette-based approaches is the reduction of data dimension since the 3D scene is represented by 2D images. In order to overcome this drawback, a depth camera is often employed. One of the devices that are widely used is the Microsoft Kinect. Beside its low price, this camera provides a built-in functionality of human skeleton localization, estimated in each single depth frame [13,14]. Such skeletal information is useful for gait-related problems such as abnormal gait detection [15], gait-based recognition [16], and pathological gait analysis [17]. A

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limitation of skeleton-based approaches is that the skeleton may be deformed due to self-occlusions in the depth map. Unfortunately, such problem usually occurs in pathological gaits [18,19]. For that reason, other researchers have used depth images without skeleton fitting to perform gait assessment. Auvinet et al. [19] proposed an asymmetry index obtained with a depth camera (Microsoft Kinect). It is based on the longitudinal spatial difference between a specific zone of the left and the right legs at comparable times within their respective step cycle. Mean depth images representing the most representative (averaged) gait cycle for each subject are used to decrease the influence of noise. However, this method is limited to a small part of the lower limbs and requires the detection of gait cycles. Nguyen et al. [20] have also employed successfully (enhanced) depth maps for gait assessment using a weighted combination of a PoI-score, based on depth map key points, and a LoPS-score describing a measurement of body balance from the body silhouette. However, their method was still limited to a partial view of the body and basic features.

Taking all this into account, we present an original approach that estimates an index of human gait symmetry without requiring skeleton extraction or gait cycle detection. To improve the performance, the input of our system is a sequence of 3D point clouds of the whole body obtained with a combination of a depth camera and two mirrors. Cylindrical histograms corresponding to point clouds are then computed and analysed for left-right symmetry for subjects walking on a treadmill to obtain their symmetry index. The remaining of this paper is organized as follow: Section 2 describes details of our method including the setup, point cloud formation, feature extraction, and gait symmetry assessment; our experiments, evaluation, and discussion are presented in Section 3, and Section 4 gives the conclusion.

2. Proposed method

In order to give a visual understanding, an overview of the proposed approach is shown in Fig. 1.

2.1. Point cloud formation

Beside a ToF depth camera and two mirrors, our setup also employs a treadmill where each subject performs his/her walking gait. The ToF camera is put in front of the subject and the two mirrors are behind so that the walking person nearly stands at the center [see Fig. 2 (a)]. An example of such captured depth map is presented in Fig. 3.

There are two popular types of depth sensor that are distinguished based on the scheme of depth estimation: structured light (SL) and Time-of-Flight (ToF) [23]. In our work, the second type was employed because it is more accurate [24] and consequently its point cloud has a higher level of details compared with the first one.

As shown in Fig. 3, each captured depth map provides subject's images from 3 different view points. In practice, the 3D reconstruction of a point cloud representing a subject's posture could also be performed when the depth camera is replaced by a color one. However, the process of reconstruction based on such data produces an object (visual hull) that is bigger, less accurate and contains redundancies as illustrated in Fig. 2(b). Therefore employing a depth camera in our setup is advantageous to provide a better model of 3D information.

Let us briefly describe the formation of a 3D point cloud from each depth map captured by a depth camera in our work. According to the example shown in Fig. 3, a depth map contains 3 partial surfaces of the subject. A point cloud representing the walking person can thus be formed by combining (a) the direct cloud (highlighted by the middle ellipse) and (b) reflections of two indirect ones (smaller ellipses), which are behind the mirrors [21,25]. The reflection of the two clouds is performed based on the equations of the two mirror planes that are determined from the positions of markers mounted on the mirror surfaces. We used the method described in Ref. [21] because it was specifically designed for ToF camera and is robust to unreliable points caused by unwanted multiple reflections. The reported reconstruction RMS errors obtained when experimenting on geometric objects were less than 5 mm. Fig. 4 illustrates an example of a 3D point cloud obtained with the setup in Fig. 3.

2.2. Feature extraction

In order to perform gait symmetry assessment, we separate the entire point cloud with a sagittal plane (perpendicular to the z-axis (coordinate system in Fig. 5) and passing through the point cloud centroid) into two non-overlapping half-point-clouds corresponding to the left and right half-bodies. In practice, each individual point cloud is processed to obtain a cylindrical histogram, and then the histogram is vertically split into two sub-histograms representing two half-bodies (see below).

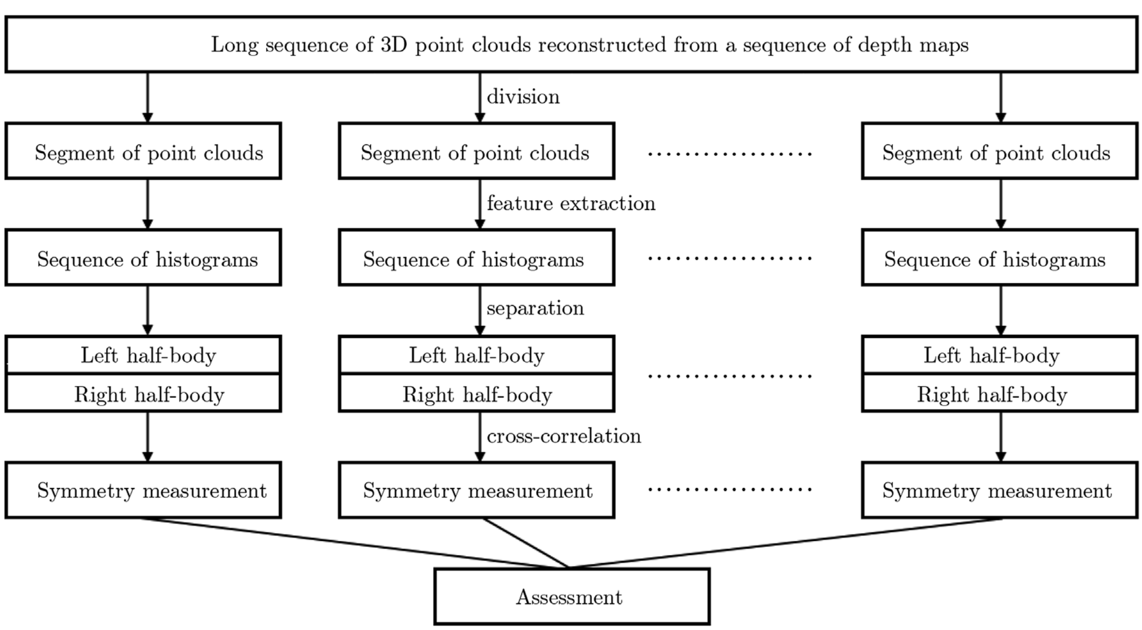

Fig. 1. Flowchart of our processing.