Gait Analysis for Criminal Identification Based on Motion Capture

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Abstract: The need for criminal identification is becoming ever more critical with the increasing number of crime occurred in our vast society. As numerous identification techniques are being used for many civilian and forensic applications, gait and its features have evoked considerable interest. The literature confirmed that accurate results can be found in gait identification using motion capture approach, especially in the critical area of clinical and sport application. By using motion capture technique, some difficulties in acquiring precise data can be avoided as the motion capture system captured the exact coordinate of each body points. In this research, a new mechanism of criminal identification is proposed by using person’s gait as a case study. The system was developed based on normalization method and Principle Component Analysis (PCA) which optimizing the features extracted from the gait motion data. The principle components obtained were then being matched using Euclidean Distance method between the sample and suspect data. Results from the experiments show that the proposed system is capable in identifying the person based on their gait by matching the sample and suspect motion files and presented the most probable person as a strong evidence for criminal identification.

Keywords: Gait Identification, PCA, Motion Capture, Euclidean Distance.

1. Introduction

In recent years, the scariness of criminal identification of the suspect has made the investigation environment very difficult. However, with the influence of technology, methods of identification have evolved. The identification using traditional techniques of eyewitnesses has changed to an advance technique based on physical and behavioural characteristics of an individual to establish identity. Gait recognition studies have encouraged various researches in computer vision to gain potential gait signatures from images for the purpose of identifying people.

The gait analysis aim is to understand human behaviours which specifically involve the process of analyzing the human image sequences for detection, tracking and recognition of people. Johansson [1] and Stevenage et al. [2] have confirmed that gait signatures extracted from video can be used as a consistent cue to identify individual. Gait's advantages are that it is non-invasive, and it appears to be difficult to camouflage, especially in cases of serious crime. Therefore with reasonable accuracy provided by the analysis, gait can be used in forensic such as prison security and criminal identification and also has a big potential to be implemented in wide range of civilian application areas.

Motion capture has been identified as one of the technique to record a person’s gait. According to Glardon, Boulic and Thalmann [3], motion capture is a method for capturing the actor's real time performance or a different kind of real time motion input. David and Patrick [4] describes that motion capture can also be applied in several disciplines such as human–computer interface, games, video surveillance, animation, interaction with virtual environment.

Current motion capture systems, based on state-of-the-art hardware and software, allow transferring human movement to a three-dimensional (3D) biomechanical model that can then be manipulated in various ways, thus offering a wide range of possibilities. Bouchrika et al. [5] employ state of the art mocap system to work in real surveillance systems to recognize walking people over different views. This is a practical step to use motion capture in identifying the criminal that is captured using cctv within individuals and crowds. Furthermore, with the ease of utilizing motion capture approach in gait analysis, the identification rate may result in a positive range. Thus, the goal of this research is to apply gait analysis towards criminal identification based on motion capture.

2. Gait Analysis

While there are many types of gait, such as walking, crawling, jogging, running and skipping, the action that is focused is only on human walking. There are some features in a person’s gait that are common for everyone. Jain et al. [6] identified that human gait can be divided into gait cycles, that is the time gap between consecutive instances of initial foot-to-floor
contact ‘heal strike’ for the same foot. The gait cycle consist of three tasks, namely the weight acceptance, single limb support and limb advancement. The most studied gait features since 1970s is the lower limb. Research conducted by Liu et al. [7] represented that by focusing only on the leg recognition performance, the identification rate is nearly equivalent to performance based on full body. Stevenage et al. [2] also strengthen the proof of legs motion that can be used as a cue to identify a person. The method can be successful for video analysis, where other parts of the body are covered by clothes but legs are easier to differentiate. The positive developments of gait study have proven that gait can become a reliable source for recognition and identification.

2.1 Recognition By Gait

The notion of using gait to recognize people continue with the gait analysis performed by Niyogi and Adelson [8]. Here, the gait signature of 2D video footage of a walking person was being analyzed. The patterns were then being examined to outline the contour of walking figure. A more accurate gait analysis with 85% of recognizing rates were achieved from this approach.

Later, optical flow was used to obtain a gait signature [9]. An individual recognition was accomplished by analyzing the shape of motion of a human walking. Moreover, BenAbdelkader et al. [10] and Bobick and Johnson [11] continue the research on automatic gait recognition which highlighted the self-similarity to fulfill identity recognition. Gait recognition technique using 3D approaches was presented by Bhanu and Han [12]. This method uses a large number of digital cameras to capture the parameters from limb movement for identification. The 3D data reconstruction is accomplished after the process of camera calibration.

2.2 Silhouette Quality and Gait Recognition

In most of gait recognition methods, recognition features are extracted from silhouette images. One of the major problems on the posture estimation using the silhouette image analysis is the overlapping of the body parts silhouettes [13]. Area overlap is commonly used as a distance measure between observed and synthesized silhouettes. Sarkar and Liu [14] described the discrimination between the background and foreground (subject) influences the silhouette quality. Some factors like unavoidable movements in the background, appearance of shadow artifacts and varying illumination due to shifting cloud cover makes silhouette segmentation in outdoor sequences complicated. Hossain et al. [15], indicated subject discrimination capability reduce for the part that is affected by the moderately change of silhouette, which is caused by the different types of clothes between a gallery and a probe. Shape ambiguities can rise along the depth direction. Jin-shi Cui and Zeng-qi Sen [16] indicate that despite the insensitive to measurement ambiguity, the features affect the precision of the information.

3 Method

In order to achieve the objectives of this research, we carried out experiments on human walking as gait analysis by using a motion capture system.

3.1 Data Collection

A collection of human gait motion was collected at Pusat Pembangunan Maklumat dan Komunikasi, Universiti Putra Malaysia (UPM) using OptiTrack Arena © motion capture system. In this research, eighteen OptiTrack FLEX: V100 camera are utilized to capture the lower limb of gait motion. The data gathering process is performed by three actors to collect the sample data as well as the suspect data to be analyzed for the purpose of criminal identification. The data obtained will then be processed and manually segmented to get the complete one (1) cycle gait data.

3.2 Data Collection

In this research, the selected part of human skeleton to be analyzed for gait motion is the lower limb. The lower limb motion sequence (gait motion), $M$ can be segmented to $n$ number of frames. Each frame defines a lower limb posture whereby a posture is a combination of the position of nine measured points as shown in Figure 1. The raw data of motion sequence $M$ which is captured from the samples and suspects are multidimensional and multidirectional. In order to test and match the suspect data to a particular sample data in database, a common condition i.e. common space, movement direction and movement cycle need to be prepared. Both the sample and suspect motion sequence $M$ shall be segmented to one gait cycle (one complete cycle).

One gait cycle starts from stepping forward the right leg followed by the left one and finish with the right step. It consists of the support of right leg, the swing of left leg, the support of both legs, the swing of right leg and the support of right leg. Then, the motion data for each parameter are normalized to make sure the constant data are prepared.
Figure 1. Nine measured points of lower limb

The data captured are then being processed using Principle Component Analysis (PCA) to obtain feature vectors of each the dataset. We then used Euclidean distance to determine the similarity of compared datasets. The result of each comparison made known as the similarity scores will tell whether a certain combination of data simplification, data analysis and data comparison is capable of detecting the percentage of gait similarity for the purpose of criminal identification.

4 The Proposed Method

The proposed method performs identification based on the following processes.

4.1 Position Normalization

Each identity (samples and suspects) has their own motion sequence $M$. Each of these motion sequences could head to a different direction to each other. Hence, all the motion sequences $M$ need a normalization transformation so that they can be tested, matched and verified to each other in a common condition (common direction or movement). The normalization is done in two stages; translation normalization and rotation normalization.

In translation normalization, each coordinate in motion sequences $M$ is shifted to a reference point i.e. at 0,0,0. The normalization is explained in equation:

$$\mathbf{v}_{\text{tn}} = \mathbf{v}_{\text{pi}} - \mathbf{v}_R , \quad i = 0,1,2,3,\ldots,n-1$$

Where $\theta$ is referring to angle of rotation required. It can be derived from the following equation

$$\tan \theta = \frac{v_{fwd}(x)}{v_{fwd}(z)} , \quad \theta = \tan^{-1}\frac{v_{fwd}(x)}{v_{fwd}(z)}$$

where $v_{fwd}$ is the forward vector that refers to the movement direction of the motion sequences $M$. $v_{fwd}$ is a cross product of two vector:

$$v_F = v_{R\rightarrow Rh} \times v_{R\rightarrow Lh}$$

4.2 Transformation to PCA (Principle Component Analysis)

The normalized motion sequence $M_{\text{norm}}$ is still in a form of high dimensional data which is difficult to analyze (curse of dimensionality). Principle Component Analysis (PCA) [17] is used to reduce the multidimensionality of the data. By using PCA method, only the significant components of data are considered and the less significant ones are being disregard.

Firstly, get the mean vector:

$$\bar{M}_{\text{norm}} = \frac{1}{n} \sum_{i=1}^{n} \mathbf{p}_i$$

Then calculate the covariance;

$$C_{\text{norm}} = \frac{1}{n} \sum_{i=1}^{n} (\mathbf{p}_i \ast \mathbf{p}_i^T - \bar{M}_{\text{norm}} \ast \bar{M}_{\text{norm}}^T)$$

From the covariance result, determine the Eigenvalue and Eigenvector:

$$\text{Covariance} \ast \text{Eigenvector} = \text{Eigenvalue} \ast \text{Eigenvector} \quad C \ast \mathbf{V} = \lambda \ast \mathbf{V}$$

Where $\lambda$ = eigenvalue and $\mathbf{V}$ is the eigenvector.

Finally, the normalized data is projected to PCA space through the following equation:

$$M_{\text{PCA}} = \mathbf{V}^T (p_i - \bar{M}_{\text{norm}})$$

A number of most significant components are then selected to be analyzed while the rest with less significant components are ignored. Hence, the dimension of the motion sequence data is reduced. This is the final step in preparing the data to be compared, tested and matched to each other.
The gait identification approach consists of the following steps:

1. **Step 1: preparing the data**
   The motion capture files were manually segmented into two categories, the first category is the sample data that consists of 3 (three) main files and the second category is the suspect data consists of 9 (nine) individual files representing three different performers. Each file contained 46 frames of gait motion sequence that is sampled at 30 frames per second.

2. **Step 2: normalization**
   Firstly, the translation normalization algorithm is computed by shifting one reference point (out of nine measured points) to the centre of the three dimension coordinate \((x,y,z) = (0,0,0)\). Then, rotation normalization is performed by first calculating the forward vector using equation (6). The forward vector shall be rotated at angle \(\theta\). That shall be first obtained through equation (5). The angle \(\theta\) is then used to calculate coordinate for rotated x and z through the equation (2) and (3) respectively. The output of the calculation is a rotated coordinate of x-axis and z-axis. The rotation angle is measured from the \(v_F\) direction to the positive Z-axis.

3. **Step 3: feature extraction (PCA transformation)**
   The mean vector is calculated after the outputs of normalization are obtained using equation (7). The next step is to calculate the covariance of the data that is derived from the following equation (8). The output of the equation (16) is a \((n \times n)\) symmetric real matrix where \(n\) is the dimension of vector \(P_i\). In this case, the symmetric real matrix is a matrix of \(46 \times 46\). Each square matrix has its own eigenvalue and eigenvector. Each eigenvalue is associated to its eigenvector which can be acquired using equation (9). Then the normalized data is projected to PCA space through the equation (10). After the principle component of motion data selected, the less significant components that are leave out will be count for error calculation using equation (11).

4. **Step 4: feature matching**
   The data of sample and suspect is retrieved before the data comparison is computed. Then, Euclidean Distance method is used to compare the two sets of data of sample and suspect using equation (12). After the Euclidean distance is calculated, the next step is to compare with other pairs of Data, up to maximum 3 Suspects vs. 3 Samples at each time. This process is a comparison between the Euclidean Distance of one motion sequence (in PCA space) to another.

5. **Step 5: identification**
   Similarity Matrix is constructed by subtracting sample data with suspect data in PCA space. Ideally, the calculation will return a \((46 \times 9)\) matrix of “0” because this pair is of the same identities. However, it is definitely impossible for any identity to walk exactly in a same sequence and coordinate repeatedly. The result is then transformed to Matrix Binary. The value of each matrix coordinate will be translated to “1” if the value is more than the threshold. Otherwise, the matrix is translated to “0”. The similarity check is done by calculating the number of “0” in the Matrix Binary. When more percentage of “0” obtained, it indicate that the matching rate is higher. A comparison of similarity matrix result was done by repeating the same processes of constructing the binary matrix for other suspects and finally the highest percentage proved the matching identity.

5. **Results and Discussion**

This section represents the experimental results of matching the sample and suspect. The matching is categorized into two ways; which is matching the same person and matching different person. As stated
earlier, the experiment is conducted for three performers known as Alice, Bob and Eve. Based on the result achieved, the identification rate is also been analyzed to evaluate the accuracy and the effectiveness of the proposed method. Another finding discovered during the experiment is the capability of identifying the most significant pattern of gait movement. Further discussion on this analysis has been included latter in this section.

5.1 Result Analysis on Similarity Matching
This section analyzed the experiment results when matching is done to the same person and also to different person. The results were obtained from the Euclidean distance as explained in the previous chapter. The experiment was conducted for each performer and the findings are presented as the followings:

Table 1. Result of matching three performer’s data against each other.

<table>
<thead>
<tr>
<th></th>
<th>Alice1</th>
<th>Alice2</th>
<th>Alice3</th>
<th>Bob1</th>
<th>Bob2</th>
<th>Bob3</th>
<th>Eve1</th>
<th>Eve2</th>
<th>Eve3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice (Sample)</td>
<td><strong>1494.9</strong></td>
<td><strong>2454.6</strong></td>
<td><strong>1615.4</strong></td>
<td>2549.5</td>
<td>5984.4</td>
<td>4275.3</td>
<td>5903.4</td>
<td>4655.2</td>
<td>5618.2</td>
</tr>
<tr>
<td>Bob  (Sample)</td>
<td>6501.2</td>
<td>4783.5</td>
<td>6792.7</td>
<td><strong>1153.5</strong></td>
<td><strong>2893.8</strong></td>
<td><strong>2500.3</strong></td>
<td>6455.7</td>
<td>5278.1</td>
<td>6181.2</td>
</tr>
<tr>
<td>Eve  (Sample)</td>
<td>4976.9</td>
<td>6905.6</td>
<td>4750.0</td>
<td>6918.1</td>
<td>4169.6</td>
<td>4894.1</td>
<td><strong>1835.5</strong></td>
<td><strong>1495.7</strong></td>
<td><strong>2315.5</strong></td>
</tr>
</tbody>
</table>

Figure 2. Result comparison of matching Alice’s sample data with the suspects data. The green bar indicates the matching result of sample with the same suspect.

Figure 3. Result comparison of matching Bob’s sample data with the suspects data. The green bar indicates the matching result of sample with the same suspect.

Figure 4. Result comparison of matching Eve’s sample data with the suspects data. The green bar indicates the matching result of sample with the same suspect.

The similarity graph illustrated individually for Alice, Bob and Eve in Figure 2, Figure 3 and Figure 4 shared common findings where the similarity value for each person indicates the lowest value when the sample data are compared with the same person as sample for the suspects. From the results, it is clearly demonstrated that matching the same person’s data (which were highlighted in yellow in the table) provides minimum similarity value compared to the data that matched with different persons.

5.2 Evaluating the Identification Rate
As described in previous chapter on how the outputs of Euclidean distance are measured, the minimum similarity value indicates the high possibility of the suspect matches the sample data. The most minimum value of distance obtained indicated the most matches suspect gait data with the sample. Another way of evaluating the identification rate proposed in this research is by constructing the similarity matrix using matrix binary. The percentage of identification can be identified by from the number of matches’ value “0” that has been translated for each matrix coordinate.
based on the threshold. Based on the binary matrix comparison generated, the percentage of similarity showed the highest score corresponding to the value of the output generated from Euclidean distance computational. Table II showed the similarity percentage of each comparison. These findings demonstrated that the computed motion capture data are capable in providing effective and accurate identification.

<table>
<thead>
<tr>
<th>Suspect</th>
<th>Distance</th>
<th>Percentage (%)</th>
<th>Distance</th>
<th>Percentage (%)</th>
<th>Distance</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alice</td>
<td>1494.9</td>
<td>83.82</td>
<td>2549.5</td>
<td>71.26</td>
<td>5903.4</td>
<td>67.9</td>
</tr>
<tr>
<td>Bob</td>
<td>2909.1</td>
<td>72.95</td>
<td>2893.8</td>
<td>85.99</td>
<td>6181.2</td>
<td>75.36</td>
</tr>
<tr>
<td>Eve</td>
<td>4976.9</td>
<td>68.12</td>
<td>4169.6</td>
<td>69.08</td>
<td>2315.5</td>
<td>73.43</td>
</tr>
</tbody>
</table>

5.3 Evaluating the Most Significant Pattern of Motion Sequence

A motion sequence of lower limbs is measured at 9 points which is at root, right hip, left hip, right knee, left knee, right ankle, left ankle, right ankle end and left ankle end. The lowest end of both limbs swing more significantly as compared to the upper end. It is visually observed through the Autodesk Motion Builder 2010 as shown in Figure 5.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Distance</th>
<th>Percentage (%)</th>
<th>Distance</th>
<th>Percentage (%)</th>
<th>Distance</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
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6. Conclusion

In this paper a new mechanism of criminal identification by recognizing a person based on their gait was proposed. A prototype of gait motion capture system has been developed which performed processes of normalization, feature extraction, feature matching and identification. Principle Component Analysis (PCA) has been applied to guarantees that only important features of the lower limb gait data are extracted. The system uses the Euclidean distance method as a means to access the most minimum distances which indicate the possible suspect that matches with the sample data. Also, the highest percentage of similarity matrix is considered as another way to identify the matches gait data between the sample and the suspect. The implementation of the proposed algorithm has been tested and the results obtained have demonstrated that the system has delivered its intended functions for optimizing the feature extracted from the motion capture data and finding the most possible suspect after similarity matching process is executed.

However, this research was carried out with limited number of performers. Larger gait data set can be created to provide a better analysis on the effectiveness of gait motion capture for identification.

In addition, the research indicates that the most significant pattern movement which can distinguish a person from others is the ankle movement. Future work can be done to the specific motion gait that shows the most significant pattern in measuring the joint position, angles and the velocity.

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References


