A Wearable Acceleration Sensor System for Gait Recognition

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Abstract-**This paper addresses the problem of human recognition based on their gait acceleration signal characteristics produced by walking. A portable microprocessor-based data collection device was designed to measure the three-dimensional gait acceleration signals during human walking. The system consists of a tri-axial accelerometer, a MCU, 32M bytes of RAM, and a data transfer module for data transfer. The device was fixed to the user's waist and three-dimensional acceleration signals were recorded at a sampling rate of 250Hz. After completing the recording, data stored in the RAM were transferred to a personal computer for wavelet denoising, gait cycles dividing, and gait pattern extracting. Through the analysis in time domain and frequency domain, and using dynamic time warping to deal with the problems result from naturally occurring changes in walking speed, 1-nearest neighbor is used for individual identification. Experiments were performed on 21 subjects walking on their normal speed. The methods of gait analysis in time domain and frequency domain are applying, the equal error rate of 5.6% and 21.1% are achieved respectively. Our preliminary results indicate that it is possible to recognize users based on their gait acceleration.**

I. INTRODUCTION

Gait recognition is currently one of the most active research topics in the domain of biometric identification. The strong interest is driven by a wide spectrum of promising applications in many areas and the increasingly emphasis of human-friendliness in the intelligent system's area. As for a kind of behavioral biometric feature, gait recognition has been researched for recently years [1]. There are many studies devoted to gait recognition, the mainstream gait studies are based on machine vision, but the influence of illumination, the shadow of the moving subject, etc are the obstacle for the vision based gait recognition, the performance of the vision based gait recognition is not very high.

Unlike the traditional research methods, this paper recognizes individuals by analysis gait acceleration signals in time domain and frequency domain. In order to capture the three dimensional human gait acceleration signals during human walking, a portable microprocessor-based data collection device was designed, and gait acceleration signals in the three directions: vertical, backward-forward and lateral were measured when the device was fixed to the user's waist. Through dividing the signal into gait cycles, the gait patterns which represent gait feature of users can be extracted, and individuals can be recognized based on the signal analysis in time domain and frequency domain. The general idea we used for recognition is template matching, while dynamic time warping (DTW) [2] is used to deal with the problems result from naturally occurring changes in walking speed.

Acceleration signals of human gait are first used in the fields of medical and motion analysis. The researches mainly used for recognition of various human activities or the feature of the motion [3, 4], such as walking, walking up/down the stairs/slope, estimation of speed and incline of walking, evaluation of the recovery of the patients, etc. Identifying users from gait signal for personal devices were first proposed by H. Ailisto [5]. Through in [5, 6], another approaches of gait recognition which use acceleration data are described, our approach use different hardware circuit, the sampling rate we use for collecting data records acceleration signal is different. Additionally, the method of remove noises from the output of gait collection device and the method for identification are different.

The remainder of this paper is organized as follows. Section II describes the gait collection device. Section III presents the experimental designs. Section IV introduces the method of signal processing based on wavelet denoising. The methodology of identifying people with accelerometer is outlined in Section V. Experimental results are described and discussed in Section VI. Section VII concludes this paper.

II. GAIT COLLECTION DEVICE

In order to capture the acceleration signals during human walking, we designed a portable microprocessor-based data acquisition system which consisted of a tri-axial

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accelerometer, a MCU with high speed 12-bit ADC, 32M bytes of RAM, and a data transfer module for data transfer. The electrical based board is shown in Figure 1.

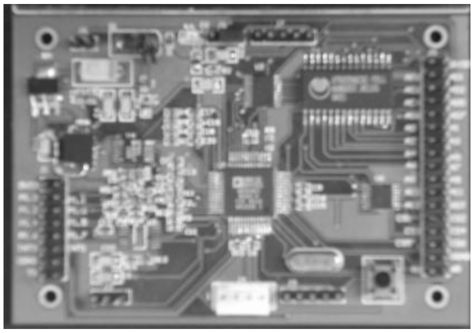


Fig. 1. Electrical base board of the gait collection device

The tri-axial accelerometer (MMA7260, Freescale, USA) was used to measure the backward-forward (X-axis), lateral (Y-axis) and vertical (Z-axis) accelerations. The MMA7260 [7] low cost capacitive micromachined accelerometer features signal conditioning, a 1-pole low pass filter, temperature compensation and g-select which allows for the selection among 4 sensitivities: $\pm 1.5g$, $\pm 2g$, $\pm 4g$ and $\pm 6g$. When the sensitivity of $\pm 1.5g$ is selected, the highest sensitivity of 800mV/g could be got. MMA7260 provides a sleep mode that is ideal for battery operated products. Three dimension gait acceleration signals acquired by MMA7260 were transformed to the microprocessor (ADUV841, ALOG, USA) for next processing. ADUC841 [8] is complete smart transducer front ends, that integrates a high performance selfcalibrating multichannel ADC, a dual DAC, and an optimized signal-cycle 20 MHz 8-bit MCU (8051 instruction set compatible) on a signal chip.

The outputs of MMA7260 were analog signal, they should be transformed to digit signal via the built-in ADC of ADUC841. The output voltage of MMA7260 was 0.45-3.65V, while the input voltage of built-in ADC of ADUC841 was 0-2.5V, the voltage matching between them should be considered. We used potentiometer resistance for the voltage matching. The circuit diagram is as figure 2.

In the interface of MMA7260 and ADUC841, removing the clock noise is important. RC filters were used on the outputs of the accelerometer to minimize clock noise (from the switched capacitor filter circuit). The sampling rate was 250Hz, and all output data of the microprocessor ADUC841 were stored in the RAM. After completing the recording, the data stored in the RAM were transferred to a personal computer via data transfer module for further processing.

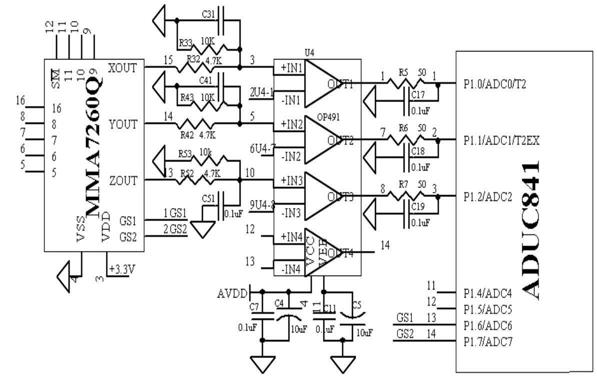


Fig. 2. The interface circuit diagram between MMA7260 and ADUC841

III. EXPERIMENTAL DESIGNS

The portable device was placed in a waist belt and located on the user's back, close to the center of gravity of the body in the standing position, just like the user carried his mobile phone. Twenty one volunteer healthy subjects (11 males, 10 females, age 19-40 years, height 150cm-179cm, weight 42Kg-70Kg, see Table 1) walked naturally along in the hallway, wearing their own flattie and without receiving any special instruction. They walked about 30m at their own normal speed; the total recording time does not exceed 5 minutes. Each volunteer tested naturally 5 times during three weeks. So the experiment contained 105 genuine trials.

Table I
Basic information of test users

ID	Sex	Height (cm)	Weight (Kg)	Age
User0	F	158	51	26
User1	F	157	56	27
User2	M	166	62	28
User3	M	170	65	24
User4	M	176	68	22
User5	M	179	70	27
User6	M	170	66	24
User7	M	173	67	21
User8	F	171	59	27
User9	F	156	42	38
User10	M	171	62	32
User11	M	167	65	21
User12	M	165	59	34
User13	M	175	67	21
User14	M	166	55	29
User15	F	157	58	32
User16	F	170	62	22
User17	F	150	49	22
User18	F	160	52	25
User19	F	165	63	28
User20	F	164	60	40

The obtained gait data from these walking trials were divided into two parts randomly. Since each user has 5 sets of experimental data, we select a set of test data randomly for each user separately to form the training data set. The data sets contained 21 genuine trials which according to 21 different users were used for training set, while the rest experimental data of 5 data sets which contained 84 (21×4) genuine trials acted as the test set. The templates generated from the training set were compared against the verification samples in the test set. This way, it was possible to simulate one genuine verification trial and 20 impostor trials for each test user, which in total 84 genuine and 1680 imposter trails.

IV. SIGNAL PROCESSING

Measured acceleration signals are low-frequency component. Actually, the output signals of gait acceleration are easy to be affected by testing environmental noise, such as electronic noise in the equipment, high-frequency noise, etc., which will obscure or reduce the clarity of the acceleration signals. During breath, however, the accelerometer does not only measure the gravitational acceleration but also the acceleration of light oscillation brought by human body, denoising of the raw gait signal is necessary. Since wavelet analysis uses a nonlinear threshold method to suppress the noise in scale spaces, its denoising effect is always better than digital filters which have an essentially fixed frequency response.

We use the wavelet transform for noise reduction in raw gait signal. The key point for suppressing noise using wavelet analysis technique is how to construct dimension function of frequency and reconstruct the waveform. Among the wavelet-packet-based methods, Daubechies wavelet of order 8 is seen to remove the noise more effectively than others. Experimental results show that after the wavelet denoising, the noise is reduced effectively, the sharp edges and details are preserved, and original gait features are preserved. It is also helpful for the following automatic gait cycle divided.

V. GAIT RECOGNITION METHODS

According to the early medical studies [9] human gait contains the information of identity; studies in psychophysics [10] also reveal that people can identify people from even impoverished displays of gait. All these shows that there exists identify information in gait signal.

The principle of identifying users from gait accelerator signal is presented in figure 3. The three-dimensional acceleration signals associated with user's walking pattern are recorded by the gait collection device worn by the user. The acceleration data are first normalized to range -1 and +1. As for normal walk, gait sequences are repetitive and exhibit nearly periodic behavior, the user's gait signal can be divided into gait cycles, and the gait pattern can be extracted from the three dimensional acceleration signals. Through combing the analysis in time domain and frequency domain, 1-nearest neighbor can be used for individual identification.

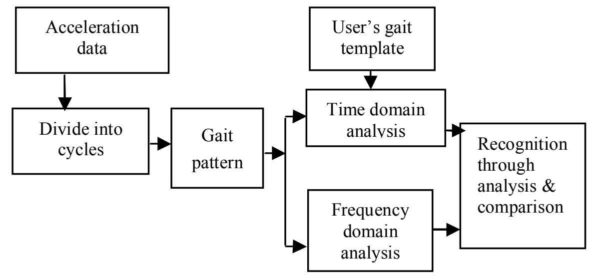
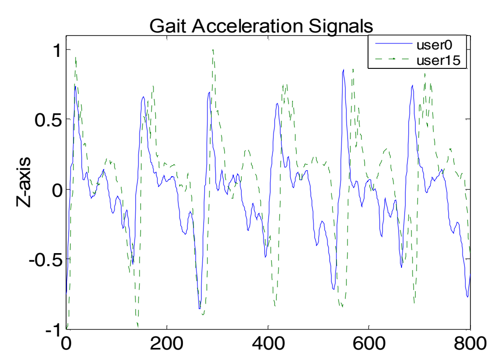


Fig.3. Block diagram of identifying users

A. *Time domain analysis*

Figure 4 shows a typical example of the time domain signals of user0 and user15. As we can see from figure 4, Z (vertical) and X (backward-forward) axis acceleration signal are repetitive and exhibit nearly periodic behavior, while Y (left-right) axis acceleration signal is less discriminative than them. For the same user, when we test in different time, the amplitude and periodic of acceleration signal in X and Z axial of his (her) normal walking are similarly very much. Contrarily, for different users, there exit obvious differences in amplitude and periodic of X and Z axial acceleration signal. As everyone owns his (her) unique shape of the gait signal, we could use graph matching to recognize different people. In time domain analysis, the acceleration signal in vertical and anteroposterior directions were used.



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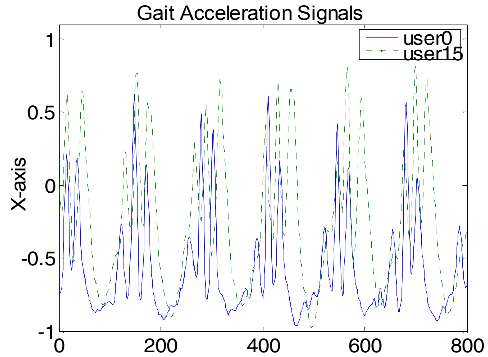

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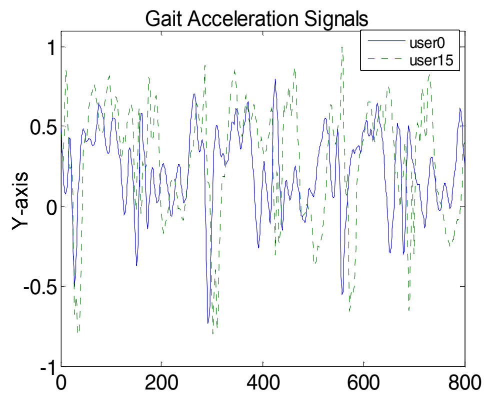


c)

Fig. 4. Z, X and Y axial acceleration signal of user0 and user15

a) vertical Z, b) backward-forward X, and c) left-right Y

However, in the case of walking, a user may change his speed from cycle to cycle. Different gait cycles tend to have unequal lengths, and the gait cycle of each user may be different. In order to identifying different individuals, dynamic time warping (DTW) method was used for matching so that non-linear time normalization should be used to dispose the naturally-occurring changes in walking speed. K-nearest neighbor is also applied for recognition; so that the individual can be recognized from a database of people whose model of gait is know a priori.

The method of time domain analysis is as follows.

1. Extract gait template for every subject from training set.

a) The three dimensional acceleration data in the training set are first divided into gait cycles.

b) Use DTW to normalize the gait cycles, so that the step length is equal.

c) Average all these one step long acceleration signal of X, Y and Z axis respectively. The averaging signal of gait cycle form the template of X, Y and Z axis: ZUserTemp(i), XUserTemp(i), and YUserTemp(i), i= 0-20. The combination of X, Y and Z axis template make up of the biometric template which we call it gait template.

2. Gait recognition

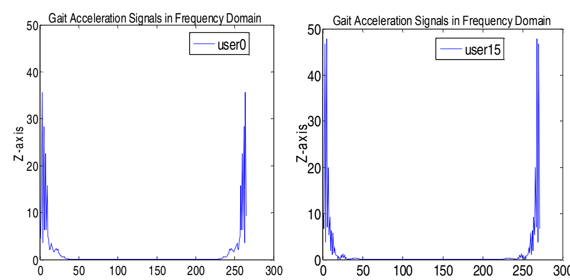
a) Deal with the three dimensional acceleration data in the test set as step 1, so that gait pattern of the test user can be got, the gait code of test user j is: ZTestTemp(j), XTestTemp(j), YTestTemp(j);

b) Match the test gait pattern and the reference gait templates by using DTW;

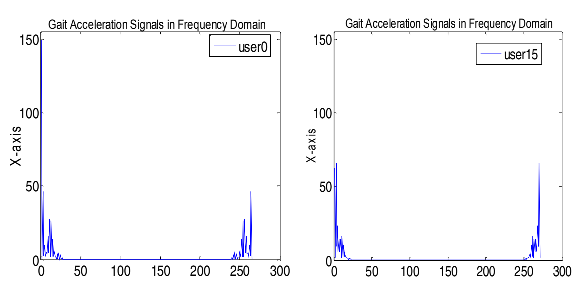
c) 1-nearest neighbor is applied for recognition.

B. *Frequency domain analysis*

Figure 5 shows a typical example of the frequency domain signals of user0 and user15. We use discrete Fourier Transformation (DFT) to turn the gait acceleration signals of time domain into frequency domain. As we did in the time domain, the three dimensional acceleration data are first divided into gait cycles, and the gait pattern of the test user can be got. After the FFT transformation of Z, X and Y axis acceleration signal, the first k feature vectors can be selected according to K-L translate, which causes $\frac{\sum_{i=0}^{k}\lambda_i}{\sum_{i=0}^{M-1}\lambda_i} \geq \alpha$. If we set $\alpha = 95\%$, k should satisfy $k \geqslant 40$. So we selected the first 40 FFT coefficients per channel as the feature vector in the frequency domain.



a)



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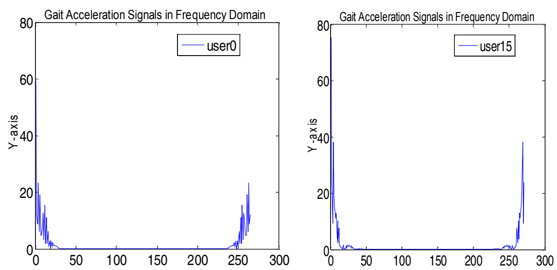

c)

Fig.5. The Z, X and Y axial frequency domain signals of user0 and user15: a) vertical Z, b) backward-forward X, and c) left-right Y

The feature vector of gait acceleration in time domain does not consider the phase information, while the feature vector in frequency domain includes the phase information. In order to match two plural vectors, we used the method of plural correlation to measure the similarity. In time domain, correlation coefficient can be used to measure the similarity. Expansion it to frequency domain, if X, Y are two plural vectors, the correlation coefficients of X and Y can calculated as follows.

$$R(X,Y)=\frac{\left|\sum_{n=1}^{N}(X-\bar{X})(Y-\bar{Y})^{*}\right|}{\sqrt{\sigma_X^2\sigma_Y^2}} \tag{1}$$

And

$$\sigma_X^2=\sum_{n=1}^{N}\left|(\mathrm{Re}(X)+j\,\mathrm{Im}(X))-(\overline{\mathrm{Re}(X)}+j\overline{\mathrm{Im}(X)})\right|^2 \tag{2}$$

$$\sigma_Y^2=\sum_{n=1}^{N}\left|(\mathrm{Re}(Y)+j\,\mathrm{Im}(Y))-(\overline{\mathrm{Re}(Y)}+j\overline{\mathrm{Im}(Y)})\right|^2 \tag{3}$$

Let $\tilde{X}=X-\bar{X}$, $\tilde{Y}=Y-\bar{Y}$, the numerator of Eq.1 can express as

$$\begin{aligned}\sum_{n=1}^{N}(X-\bar{X})(Y-\bar{Y})^{*} &=\sum_{n=1}^{N}\tilde{X}\tilde{Y}^{*}\\ &=\sum_{n=1}^{N}(\mathrm{Re}(\tilde{X})+j\,\mathrm{Im}(\tilde{X}))(\mathrm{Re}(\tilde{Y})+j\,\mathrm{Im}(\tilde{Y}))\\ &=\sum_{n=1}^{N}(\mathrm{Re}(\tilde{X})\mathrm{Re}(\tilde{Y})+\mathrm{Im}(\tilde{X})\,\mathrm{Im}(\tilde{Y}))\\ &\quad+j(\mathrm{Im}(\tilde{X})\mathrm{Re}(\tilde{Y})-\mathrm{Re}(\tilde{X})\,\mathrm{Im}(\tilde{Y}))\end{aligned} \tag{4}$$

We can see that Eq.4 include the cross correlation items of real part and imaginary part, in order to predigest operation, Eq.4 can express as

$$\sum_{n=1}^{N}(X-\bar{X})(Y-\bar{Y})^{*}=\sum_{n=1}^{N}(\mathrm{Re}(\tilde{X})\mathrm{Re}(\tilde{Y})+\mathrm{Im}(\tilde{X})\,\mathrm{Im}(\tilde{Y})) \tag{5}$$

Then the correlation coefficient of two plural vectors can calculate as:

$$R(X,Y)=\frac{\sum_{n=1}^{N}(\mathrm{Re}(\tilde{X})\mathrm{Re}(\tilde{Y})+\mathrm{Im}(\tilde{X})\,\mathrm{Im}(\tilde{Y}))}{\sqrt{\sigma_X^2\sigma_Y^2}} \tag{6}$$

Differently with time domain analysis, three dimension acceleration signals are combined for frequency analysis. We calculate the correlation coefficients of gait templates and the test subjects in frequency domain, and 1-nearest neighbor is applied for the recognition.

VI. RESULTS

Experiments were performed to evaluate the potential of our proposed methods. Figure 6 plots the Receive Operating Characteristics (ROC) curve in terms of False Rejection Ratio (FRR) and False Acceptance Ratio (FAR). The Equal Error Rate (EER) for the analysis method in time domain is 5.6%, and the EER in frequency domain achieves 21.1%. If we combine the two analysis methods, the accuracy of individual recognition can improve a little. Ailisto H [5] reported that they achieved the EER of 6.4% by using the correlation method. Their experiment contained 36 test subjects, each test subject walked in their normal, fast, and slow speeds. In their study, they thought it was a false result if different walking speeds of the same test subject were identified as the same person. Gafurov D [6] revealed that the best EER of 5% was achieved through the data distribution statistic method. Their data sets were collected from the ankle of the participants, and 21 participants walking in their normal speed at the same day.

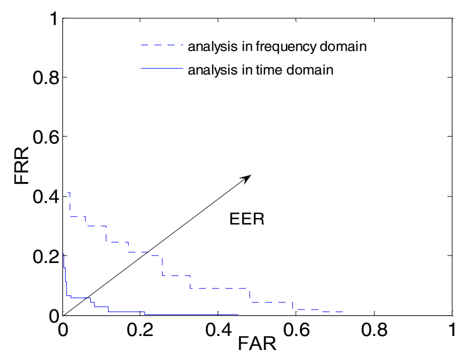

Fig. 6 Receive Operating Characteristics

When comparing our method with machine vision based gait recognition methods, our method outperforms a little. According to the studies [2, 11, 12], which all are based on video signal and persons walking on a treadmill in controlled conditions, the EER are between 8-24%. Our EER figure is comparable with each others.

VII. CONCLUSIONS

A portable microprocessor-based data acquisition system which allows gait acceleration signals to be recorded is developed. The methods of gait analysis in time domain and frequency domain are proposed, and the preliminary results indicate that it is possible to recognize users based on their gait acceleration signals. As DTW has been used, the method is found to be reasonably robust to changes in speed. The gait recognition method in this paper can be applied to smart interface, access control, and protection of mobile and portable electronic devices. Although our experimental results with a small number of users are very promising. However, further studies are required. Exploring better similarity measures, seeking more effective method of gait feature extract and analysis, optimizing the algorithm of gait recognition deserve more attention in future work.

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