Design and Implementation of a Three-dimensional Pedometer Accumulating Walking or Jogging Motions

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***Abstract*—This paper uses a three-axis accelerometer to design and implement a three-dimensional pedometer, which can determine the walking or jogging automatically. This device can count the number of steps. It can also judge the status of walking or jogging simultaneously. The three-dimensional pedometer can be worn on the user's waist or placed within pocket arbitrarily. This three-dimensional pedometer can also detect the intermittent steps. It also improves the general pedometers' judgment mechanism which the users have to exercise continuously. Some different smoothing methods is used to filter the noises of human walking reacting force. In the determination of walking and running, this paper presents the filter by walking threshold and running threshold, and designs an algorithm to switch walking mode and running mode.**

***Keywords*—Pedometer, Accelerometer, Angle Estimation**

I. INTRODUCTION

The design principle of pedometers uses vertical vibration induced by walking to drive the balancing mechanism in the pedometer. Waist motion is the most apparent source of the vibration. Thus, the number of vertical motions by the body can be determined by identifying the local peak and valley points of the curve. Different dynamic thresholds to detect the number of steps can be adjusted according to the users.

An accelerometer, which is also known as the G-sensor, is used to detect the accelerated motion of objects. It can detect instrumental vibrations and effects and can be applied to the displacement component of inertial navigation systems and in global positioning system navigation with gyroscopes. Accelerometers have been used extensively in recent years. For instance, P. H. Veltink et al. [1] placed an accelerometer on a user's chest and thigh to distinguish static and dynamic actions, such as standing, sitting, lying, walking, going up and down stairs, and cycling. J. Mantyjarvi et al. [2] placed accelerometers around a user's waist and identified body motion state by using principal component analysis, independent component analysis, and wavelet transform. The best experimental result is 83% to 90%. H. J. Luinge et al. [3] attached an accelerometer to a user's back and used a Kalman filter to improve accelerometer detection on an inclined trunk. D. M. Karantonis et al. [4] used a three-axis accelerometer to design a portable wireless device that can be worn around the waist. A single-chip microcomputer receives signals from the three-axis accelerometer, and signals are wirelessly transmitted to the computer terminal. The user's behavior state is then identified according to changes in the three-axis acceleration value. Twelve actions are measured in Karantonis et al.'s experiment, including walking, sitting, and lying down. The accuracy rate is 83% to 96%. A. M. Khan et al. [5] placed three-axis accelerometers in a user's chest pocket, trouser front and back pockets, and coat pocket. Resting (sitting/standing), walking, going upstairs and downstairs, running, and cycling motions are identified according to acceleration changes detected by the accelerometers in different positions. The detection accuracy rate of the completed identification system is 95%.

The current study uses a three-axis accelerometer to implement a 3D pedometer that automatically identifies walking and running motions. Thus, a user can conveniently measure his/her amount of exercise. A user can wear the pedometer around the waist or place it in a pocket or a backpack to detect the number of steps taken, unlike existing mechanical pedometers that must be worn around the waist. The proposed design does not require the existing fixed-second misjudgment prevention mechanism. The motion state of the user can be displayed instantly according to the experimental walking and running threshold and the walk/run mode switching algorithm in the automatic walking-and-running-motion identification function. The number of walking or running steps is accumulated.

This paper is described in five sections as follows. Section I: Foreword outlines the study theme, describes the study motive and purpose, reviews the related paper and discusses the application of the related technique. Section II: System structure introduces the hardware structure in this paper, and describes the specifications and the analysis method of each device in detail. Section III: Both of walking and jogging motions are discussed. Section IV: Experimental result

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provides full experiment data so as to measure the data for pedometer's performance, and discusses experiment results. Section V: Conclusion summarizes and discusses the findings of this paper.

II. System Architecture and Signal Analysis

This study used the three-axis accelerometer named MMA8452Q and a monolithic chip named MPC82G516. The MMA8452Q detects the acceleration values of three axes, and the inter-integrated circuit (IIC) transmits the three-axis acceleration information to the MPC82G516. The Universal Asynchronous Receiver/Transmitter (UART) transmission mode was used to transfer the three-axis acceleration values from the monolithic chip MPC82G516 to the computer terminal for convenient statistical data analysis in the experimental stage. The program in the monolithic chip of the 3D pedometer automatically identifies walking and running motions and directly calculates the number of steps. The results are finally transferred to the computer program and displayed. Fig. 1 depicts the system flowchart of the 3D pedometer with respect to the automatic identification of walking and running motions.

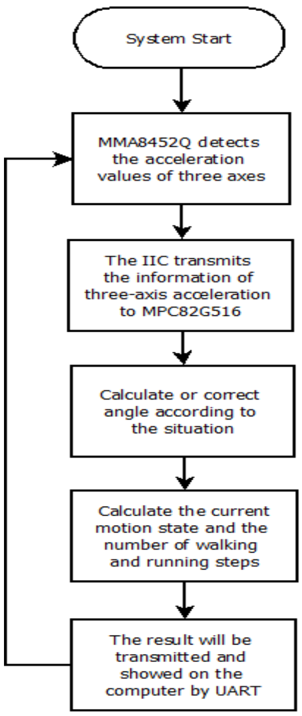

Fig. 1 System flowchart of the 3D pedometer with respect to the automatic identification of walking and running motions.

However, the inertial vibration induced by the stepping motion results in rough jitters, and the noise from the jitter influences the number of steps filtered through the threshold. Therefore, several signal smoothing processing modes, including three-point average, Hanning filter, Hanning recursive smoothing, five-point average, and five-point triple smoothing methods, were used to smooth the signal analysis experiment results, reduce signal jitter error production, and determine the differences among different smoothing techniques in walking and running detection results [6][7][8].

A. Three-point average method

The target point value and the values of two adjacent points were averaged in the three-point average smoothing method by using Eq. (1). *y(t)* is the smoothed value, *x(t)* is the original signal value at time *t*, and $t = 2,3,4,\ldots,n-1$.

$$\begin{cases} y(1)=\frac{1}{3}[2x(1)+x(2)] \\ y(t)=\frac{1}{3}[x(t-1)+x+x(t+1)] \\ y(n)=\frac{1}{3}[x(n-1)+2x(n)] \end{cases} \tag{1}$$

B. Hanning filter

The Hanning filter [8] smoothing process stresses the value of the previous point By using Eq. (2), where *y(t)* denotes the signal value after smoothing and *x(t)* denotes the original signal value at time *t*. The smoothing process is implemented after $t = 3$.

$$y(t)=\frac{1}{4}[x(t)+2x(t-1)+x(t-2)] \tag{2}$$

C. Hanning recursive smoothing technique

The recursive filter smoothing technique is designed according to the Hanning filter smoothing formula as represented by Eq. (3), where $t = 3,4,5,\ldots.n$

$$\begin{cases} y(1)=x(1) \\ y(2)=\frac{1}{2}[x(2)+y(1)] \\ y(t)=\frac{1}{4}[x(t)+2y(t-1)+y(t-2)] \end{cases} \tag{3}$$

D. Five-point weighted average method

The five-point weighted average method [9] is similar to the three-point average method. The weighted average of the target point and two adjacent points is calculated by using Eq. (4), where *y(t)* is the smoothed value, *x(t)* is the original signal value at time *t*, and $t = 3,4,5,\ldots, n-2$.

$$\begin{cases} y(1)=\frac{1}{5}[3x(1)+2x(2)+x(3)-x(4)] \\ y(2)=\frac{1}{10}[4x(1)+3x(2)+2x(3)+x(4)] \\ y(t)=\frac{1}{5}[x(t-2)+x(t-1)+x(t)+x(t+1)+x(t+2)] \\ y(n-1)=\frac{1}{10}[x(n-3)+2x(n-2)+3x(n-1)+4x(n)] \\ y(n)=\frac{1}{5}[-x(n-3)+x(n-2)+2x(n-1)+3x(n)] \end{cases} \tag{4}$$

E. Five-point triple smoothing

The five-point triple smoothing method [9] repeats least squares polynomial discrete data smoothing thrice by using Eq. (5), where *y(t)* is the smoothed value, and *x(t)* is the original signal value at time *t*, *t = 3,4,5,..., n - 2*.

$$\begin{cases} y(1) = \frac{1}{70}[69x(1) + 4x(2) - 6x(3) + 4x(4) - x(5)] \\ y(2) = \frac{1}{35}[2x(1) + 27x(2) + 12x(3) - 8x(4) + 2x(5)] \\ y(t) = \frac{1}{35}[-3x(t-2) + 12x(t-1) + 17x(t) + 12x(t+1) - 3x(t+2)] \\ y(n-1) = \frac{1}{35}[2x(n-4) - 8x(n-3) + 12x(n-2) + 27x(n-1) + 2x(n)] \\ y(n) = \frac{1}{70}[-x(n-4) + 4x(n-3) - 6x(n-2) + 4x(n-1) + 69x(n)] \end{cases} \quad (5)$$

The experimental results of the signal reading analysis are obtained by using the five smoothing techniques described above. The smoothing result shows that the five smoothing techniques can reduce the inertial vibration of the body as induced by stepping motions and stabilize walking and running behavior recognition values, which are advantageous to users. The Hanning recursive smoothing technique and five-point weighted average method have the most apparent smoothing effect out of the five techniques.

III. Walking and Jogging Motions

The running threshold must be greater than the walking acceleration change and less than the running acceleration change to recognize motion state and number of walking and running steps, respectively. Hence, motion state, number of walking steps, and number of running steps can be successfully separated. Various thresholds are used to detect 100 walking and running steps. Different smoothing techniques use various walking thresholds, and the running threshold is used to identify the walking or running motions of the user. The threshold is set at 0.2 G to 0.54 G, and the spacing is set at 0.02 G based on experimental adjustment. Different running thresholds have varied walking and running accuracy rates. Thus, the two experimental results are averaged to obtain the average accuracy rate. The optimal walking and running thresholds for different smoothing techniques are shown in Table I. The five-point weighted average method maintains a good detection accuracy rate in the running threshold experiment although the Hanning recursive smoothing technique achieves a good walking accuracy rate in various samples.

TABLE I
WALKING AND RUNNING THRESHOLDS FOR DIFFERENT SMOOTHING TECHNIQUES AND THEIR ACCURACY RATES

	Original	Three-point average method	Hanning filter	Hanning recursive smoothing technique	Five-point weighted average method	*Five-point triple smoothing*
Walk	0.18	0.14	0.14	0.04	0.08	0.18
Run	0.46	0.46	0.46	0.22	0.4	0.46
Accuracy	97%	99%	99%	81.5%	99.5%	99.5%

The walk/run mode switching system is designed to achieve a high detection accuracy rate as users typically walk or run continuously. The accuracy rate of the Hanning recursive smoothing technique in walking and running identification is thus improved. This system detects resting, walking, and running mode patterns, and the modes switch according to different conditions. The detection of two consecutive steps is considered the switching mode standard. The walking or running mode can be maintained as long as acceleration exceeds the walking threshold even if the switching mode standard is not attained.

The mode switching algorithm in the walking experiment reduces the detection misjudgment rate. Misjudgment is likely to occur in the first two steps of the running experiment, and this problem has not yet been addressed. The misjudgment rate of the mode switching algorithm, which is lower than that of the simple threshold filtering method, can be seen in other data aside from the running start problem. Therefore, the mode switching algorithm is used to calculate the number of walking and running steps in this study. The misjudgment rates of three-point average, Hanning filter, five-point weighted average, and five-point triple smoothing methods are reduced to below 2% after filtration by using the mode switching algorithm in the experiment on the misjudgment rates of various samples to select smoothing technique. The misjudgment rates of the Hanning recursive smoothing technique and the raw data without smoothing technique remain as high as 12% and 24%, respectively. The misjudgment rates of both methods with respect to the rest of the samples are relatively high. Thus, the two signal processing modes are excluded in this study.

The experiment on the accuracy rates of walking and running alternation was then conducted. Ten walking steps and ten running steps were taken alternately until the number of steps of each motion reached 100 for a total of 200 steps. The three-point average, Hanning filter, five-point weighted average, and five-point triple smoothing methods and the mode switching algorithm were used to count the steps in signal processing. The running accuracy rates of the four smoothing modes were higher than 92% on average. In the walk that is likely to be misjudged, the five-point weighted average method has the best accuracy rate. The walking accuracy rate was 89% on average, which is better than that of the other three smoothing techniques. Therefore, the five-point weighted average method was used for signal smoothing.

IV. Experimental Results and Analysis

The step counting system in walking and running recognition is tested. Different user samples wear the 3D pedometer that automatically identifies walking and running motions, which was designed and implemented in this study. The walk/run mode switching algorithm is used to prove that this pedometer can recognize the number of walking and running steps taken by the user. The detailed experimental method is described below. The walk and run alternating mode is defined as walking 10 steps before running 10 steps.

This process is alternated until 100 steps of each motion are taken for a total of 200 steps.

The experimental results are shown in Table II. The detection accuracy rate in the simple running experiment is the highest of the three walking-mode detection accuracy rates at 95% to 98.8% on average; that of the simple walking experiment is 88.4% to 92.6%; and the accuracy rate of the alternate walk and run experiment is the poorest at 71.6% to 96%. The pedometer worn around the waist achieves the highest average detection accuracy rate, followed by that in the pocket. The pedometer placed horizontally in the backpack has the worst accuracy rate of the three pedometer-wearing modes.

The average walking mode misjudgment rates of the 3D pedometer that automatically identifies walking and running motions in different wearing modes are shown to be lower than 5% according to the experimental results shown above. The average accuracy rates are higher than 70%, with the exception of the instances in which the pedometer is placed horizontally in the backpack and during the alternate walk and run experiment. The average accuracy rates are higher than 87% in these cases, thus proving that this pedometer accurately identifies walking and running motions.

V. CONCLUSIONS

A 3D pedometer that automatically identifies walking and running motions was implemented in this study by using a three-axis accelerometer. The angles included between the three axes and the horizontal plane was obtained according to the gravity component. The acceleration change in the motion direction perpendicular to the ground was obtained. Different signal smoothing processing modes and thresholds were used to filter the number of steps to implement the step counting function of this device at arbitrary angles. Running threshold filtering was proposed to calculate the number of steps separately, and the walk/run mode switching algorithm was used. This pedometer that automatically identifies walking and running motions remedies defects in generic pedometers currently available on the market.

TABLE III
RESULTS OF THE EXPERIMENTS ON THE STEP COUNTING SYSTEM IN WALKING AND RUNNING RECOGNITION

Item		**Walk 100 steps**		**Run 100 steps**		**Walk 100 steps and run 100 steps**
Walk accuracy rate /miss rate	Waist	92.6 %	0.6 %	None		87.6%
	Pocket	88.4 %	0%	None		88.8%
	Bag	89.2 %	0%	None		71.6%
Run accuracy rate /miss rate	Waist	None		98.4 %	2%	96%
	Pocket	None		95%	4.8 %	92.6%
	Bag	None		98.8 %	2.4 %	95.4%

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