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Modeling Human Walking for Step Detection and Stride Determination by 3-Axis Accelerometer Readings in Pedometer

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Abstract—**Pedometers are increasingly being used for purposes like assessment of physical activity, rehabilitation, disease management and as a utility for the visually impaired. These devices rely on an algorithm that consists of measuring distance covered by the number of steps taken. Conventional estimations of distance covered rely on empirically obtained relations to arrive at their data. In this paper, we present a means of estimating the distance covered by the wearer through a more realistic model using sensor readings from a 3-axis accelerometer present in most pedometers as well as in modern phones and tablets. The first step is step detection, where the accelerometer readings are processed and each individual step taken by the wearer is identified. Determination of stride length comes next, which is based on the inverted pendulum model and the periodicity of the accelerations generated by the human. Lastly, the discrete step lengths are integrated to obtain the distance covered over the entire course of the walk. Finally, the obtained results are analyzed with respect to currently existing models.**

Keywords-human walking; step detection; stride length; 3-axis accelerometer; sinusoidal curve approximation;

I. INTRODUCTION

Analysis of the mechanism of human walking and gait provides useful information pertaining to a number of applications such as fitness and exercise, medical studies, detection of anomalies in gait, etc. The device commonly used for the analysis of human walking is known as the pedometer. The pedometer is used in order to detect the occurrence of steps during walking. A pedometer makes use of a 3-axis accelerometer in order to measure steps during walking. This accelerometer provides the variations in acceleration along each axis, namely roll, pitch and yaw. Each step during the walking cycle entails a change in acceleration along each axis. Steps are detected by measuring the accelerometer readings, with respect to a threshold value. In addition to this, a pedometer may also provide the distance traveled during the walking session. Stride length estimation is another feature that can be implemented in a pedometer. Often, the implementation of stride length determination is based on empirical data and formulas. Seldom is a near real-time approach considered for stride length determination. Such an approach to the determination of stride length can provide a better means of determining traveled distance, applicable in a more real-time scenario. This paper serves to provide an understanding of the methods utilized in order to determine stride length in a dynamic manner. The results presented here serve to provide insight into the possible methods of implementing dynamic stride length determination, as applied to a pedometer, through analysis of the human walking mechanism.

II. MECHANISM OF HUMAN WALKING

To construct a model to estimate the features of a human step, it is first necessary to comprehend the mechanism of human walking. A complete cycle of human walking encompasses two phases: the standing phase and the walking phase.

The momentary difference between the walking and standing phases is the basis on which the step count is taken, i.e. individual steps are determined. This difference exhibits itself as a low point in the readings of the accelerometer which can be exploited to our advantage as discussed in section III. The walking phase, however, is the focus of the stride determination aspect of the pedometer as it is in this phase that the stride, and hence forward motion, occurs. The walking phase comprises of three distinct phases, as shown.

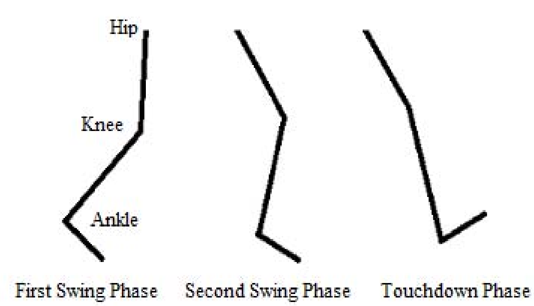

Figure 1. Representation of the three stages of a walking phase: first swing phase, second swing phase and the heel touchdown phase.

The first two phases together constitute the swing phase: the first swing phase occurs when the foot moves from the point at which it is farthest behind the COM (center of mass)

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of the body and accelerates forwards and downwards. In the second swing phase, the foot is placed in front of the COM and accelerates forwards until the touchdown. The touchdown phase occurs when the heel of the foot impacts upon the ground, which is also known as the foot-flat phase.

The accelerations along the horizontal and vertical axes, represented by A_H and A_V respectively, are showed with respect to their constituent components h, g and a in the diagrams, where:

h is vertical acceleration,
g is acceleration due to gravity, and
a is horizontal acceleration.

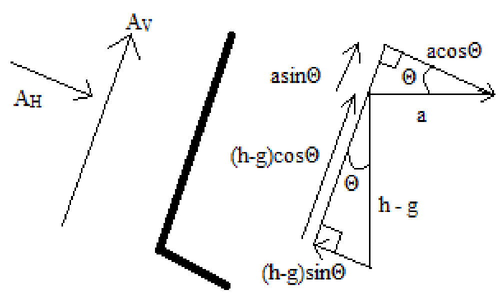

Figure 2. Representation of accelerations along the vertical (A_V) and horizontal (A_H) directions and their components in the First Swing phase of the walking phase.

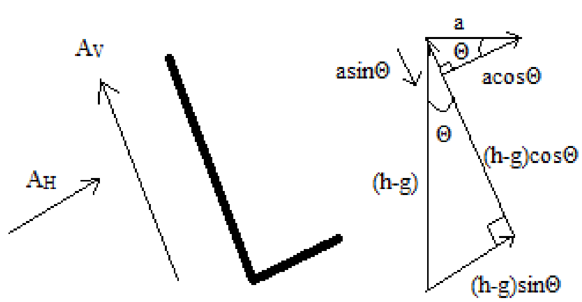

Figure 3. Representation of accelerations along the vertical (A_V) and horizontal (A_H) directions and their components in the Second Swing phase of the walking phase.

Based on the various accelerations acting in the vertical and horizontal directions as described in the graph, we are able to obtain the following relations for the resultant horizontal and vertical accelerations:

$$A_H(t)=(h-g)\sin\Theta(t)+(a)\cos\Theta(t)$$
$$A_V(t)=(h-g)\cos\Theta(t)-(a)\sin\Theta(t) \tag{1}$$

The swing phases are followed by the heel touchdown phase. In this phase, the heel first strikes the ground, followed by the sole and the toe. The repulsive action of the ground causes impact force to act upon the foot. Hence, this phase of the walking phase, while being the shortest of the three phases, is responsible for the largest acceleration values observed. A general acceleration pattern for the three phases is shown below.

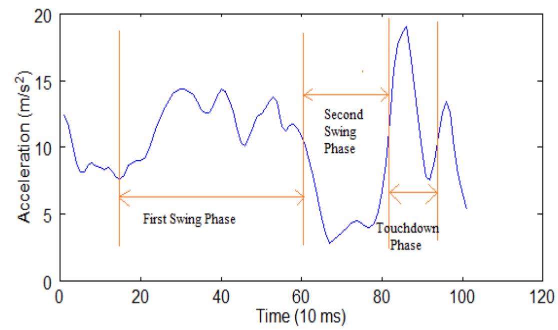

Figure 4. Representation of swing and heel-touchdown phases during walking cycle.

This mechanism of walking is utilized to analyze the obtained accelerometer readings throughout this model.

III. Detecting Step Occurrences

Pedometers generally make use of MEMS (microelectromechanical systems), or IMEMS (Integrated MEMS), in order to detect steps. MEMS, along with inertial sensors, and modern software implements, allow detection of steps with high probability. The necessary data to perform step detection is available from the accelerometer graph results. When analyzing the mechanics of human walking, we consider 3 axes of motion, namely the forward (roll), vertical (yaw), and side (pitch) axes. During walking, the accelerometer senses the acceleration along its 3 axes x, y and z. As the pedometer orientation is variable, the measurement should not stringently depend on the relationship between the motion and accelerometer axes.

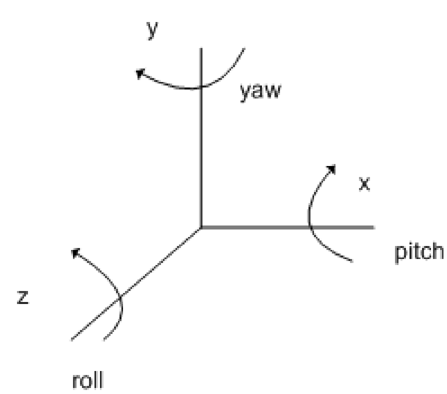

Figure 5. Representation of the three axes used in accelerometer measurements

Human stride is not constant. Step measurements and strides vary from person to person. In order to discern one cycle of walking, we consider the signal patterns of the swing phase and the heel-strike phase during the walk. The accelerometer measures the signal incurred by walking behavior. The step is counted when all phases of the walk, namely 1st swing, 2nd swing and heel touchdown, have been registered.

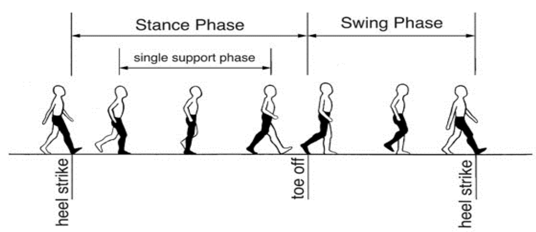

Figure 6. Representation of walking cycle, indicating phases during walking cycle

The accelerometer provides the data we require to determine the occurrence of a step. Detection algorithms can be applied to the vertical (pitch) and horizontal (roll) signals of the accelerometer graph, and a number of identification strategies can be used. Here, we consider the localized maxima, within a given fixed interval.

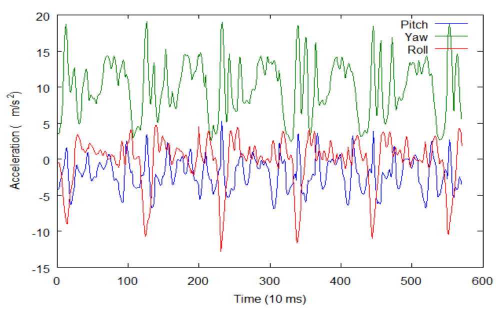

Figure 7. Accelerometer measurements during a walk

Antero-posterior (horizontal) acceleration represents one maximum, corresponding to heel impact. This physically represents the forward displacement of the body. Hence, we determine the step occurrence using shifted peaks in the accelerometer graph.

Figure 7 shows the x, y, and z measurements of an accelerometer during a walk. In order to accurately detect a step, we consider peak detection and a dynamic threshold for each of the three axes.

In analysis of the graph, we take samples of the acceleration at a fixed frequency of around, say 50 Hertz, i.e. we sample the acceleration every 20ms. Dynamically, over the range of sample values, we update the minimum and maximum values of the three-axis acceleration over a fixed interval of samples. We compute the average value (*Max + Min) / 2,* in order to obtain the dynamic threshold value. Since this value is computed over fixed intervals, it is dynamic.

Thus, as we can observe, a step is defined as having occurred if the acceleration plot has a negative slope, when the acceleration curve crosses the dynamic threshold value.

The system defined here detects steps from the x-axis, y-axis and z-axis, depending on which of these axes has the largest change in acceleration. If the changes in acceleration are too small, they are discarded. Such an implementation, while appearing satisfactory, is not without problems. Due to extraneous causes, other vibrations apart from those produced by walking, may affect the pedometer, causing undesired false detection of steps. We use a time window in order to eliminate these invalid vibrations. Assuming a maximum and minimum value for the walking pace of an individual as five steps per second and one step every two seconds respectively, we obtain a time window of 0.2 seconds to 2.0 seconds. Steps with intervals outside this time window are extraneous and should hence be discarded.

The basic algorithmic representation of the step detection process is shown in the form of a flow chart in Figure 8.

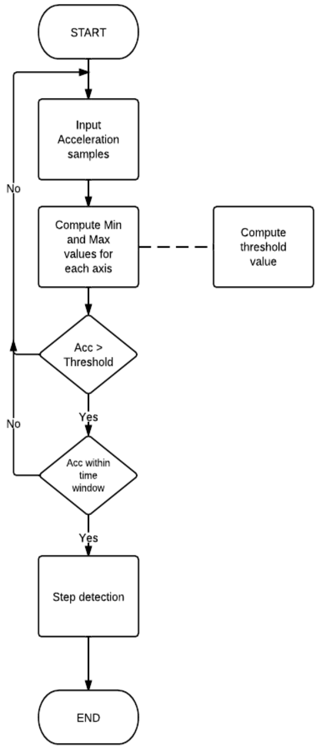

Figure 8. Representation of step detection algorithm

IV. DETERMINATION OF STRIDE LENGTH

Determination of stride length is of critical importance to the operation of a pedometer. The accuracy of the displacements measured at the step level cumulatively impact that of the result, i.e. the estimation of the overall distance covered by the user. Hence, we concentrate our efforts on developing a method to obtain an accurate estimate of the length of the individual stride while keeping within realistic constraints of complexity.

Conventional methods of analytically estimating the stride length involve directly obtaining the double integral over the horizontal accelerations observed, but however, this method has been found the be prone to integration drift error and displays significant variability between different individuals as well as differently paced strides of a single individual. In contrast, several numerical methods have also been empirically derived, and provide reasonable estimations within fixed error bars (5 - 6%)[1]. We take a different approach by using the data read from an accelerometer over the course of a single step to obtain the parameters to fit the curve of the equations encountered in (1). By employing these equations at a suitable point as explained below, we are able to obtain the degree measure of the angle of swing of the leg. Progressively integrating over the acceleration readings of a single step through the angle of stride Θ, we find the velocity measure of the motion in meters per second by approximating the derivative of degrees over time taken by the step.

From the equations in (1), we can obtain the following result:

$$A_H^2(t) + A_V^2(t) = (h - g)^2 + a^2 \tag{2}$$

The maximum and minimum amplitudes of the vertical accelerations measured, A_{VMAX} and Av_{min}, are used to obtain the angle over with to integrate the acceleration. From (1), it is evident that acceleration is maximal when the angle of swing is zero, i.e.

$$A_{VMAX} = A_{V,\,\Theta=0} = (h - g). \tag{3}$$

The corresponding value of horizontal acceleration at this stage provides us with the value of the other parameter of the set of equations as:

$$A_{H,\,\Theta=0} = a \tag{4}$$

The angle of swing Θ_S is obtained by utilizing these values of h, g and a in the system of equations (1) at a point with $A_V = A_{Vmin}$ and the corresponding value of A_H. The resulting equation for Θ is:

$$\Theta_S = \cos^{-1}\left(\frac{((h-g)A_V + aA_H)}{(A_V^2 + A_H^2)}\right) \tag{5}$$

Equivalently, Θ_S can be obtained as:

$$\Theta_S = \sin^{-1}\left(\frac{((h-g)A_H - aA_V)}{(A_V^2 + A_H^2)}\right) \tag{6}$$

The value of Θ_S thus obtained is used to calculate the integral over the forward acceleration readings from the graph to obtain a measurement of velocity over the specified time. The velocity thus obtained, originally being in meters per degree, must be converted into the corresponding value of meters per second. We can achieve this by approximating the value of the derivative of degrees over time as change in degrees divided by the corresponding change in time:

$$dt = \frac{(\Delta t)}{(\Delta \Theta)} d\,\Theta \tag{7}$$

The velocity over the horizontal, given by:

$$V_H(m/s) = \int_0^{\Theta_S} ((h-g)\sin\Theta(t) + (a)\cos\Theta(t))dt \tag{8}$$

Is obtained as:

$$V_H(m/s)=\int_0^{\Theta_s}((h-g)\sin\Theta+(a)\cos\Theta)\frac{(\Delta t)}{(\Delta\Theta)}d\Theta \quad (9)$$

This integral provides us with a real-time stride estimate value of each individual stride taken by the wearer. The overall distance d traversed is then calculated as the sum of the individual velocities for each step taken over the time taken in each particular step as represented by the expression:

$$d=\sum_{i=0}^{n} V_i t_i \quad (10)$$

In section V we present some of the results calculated through this model and the inferences drawn from the observed values.

V. Results

In the experimental setup, four sets of walks, two at normal walking pace and two jogging were taken and compared with the actual values as well as with an empirically derived formula, M4[1], which has proven to be of sufficient accuracy. The observed range of values is as presented below:

TABLE I. Deviation of Predicted from Actual values

	Min	Max
As predicted by Model	-8%	+6%
As predicted by Empirical Formulae	-5%	-4%

All values have been rounded off to the nearest percent which is inclusive of all obtained results. The results indicate that there is scope for improvement within the model through means as mentioned in section VI.

The range of values obtained for the calibrating factor, k, was obtained as:

TABLE II. Range of values Observed for K

	Min	Max
K	-1.00	+1.00

All values have been rounded off to the nearest integer which is inclusive of all obtained results. The wide range of values for k indicate the presence of various complicating factors affecting the human walk that can be accounted for in the model as explained in section VI.

In conclusion, with reference to the above results, we believe that the model as it stands is sufficient for conventional use and can provide real-time step length determinations with simplicity and efficiency.

VI. Summary and Conclusions

Step counts and stride lengths are the essential to any algorithm that aims to estimate distance travelled by an pedestrian walker or runner. As these features are intrinsically variable from person to person, any such algorithm must involve a degree of calibration and error in their measurements. However, there are various effects to be noted in the presented model as well as possibilities for improving upon the model.

- Considering the absolute maximum and minimum acceleration values in each step can lead to slight skewing of the relations in case of acceleration values that may momentarily be present but not contribute directly to forward motion. To avoid this, the maximum and minimum values can be averaged over the immediate environment, such as the immediately preceding and succeeding values in each case.

- A wide range of values for the calibrating factor indicates the presence of various factors affecting human walk as well as acceleration measurement, such as differences in body mass, height, rocking motion. Future increments of the model may include techniques of accounting for these factors.

- Stride length is not constant but instead varies over time; however, the step pattern of an individual tends to retain its form. This model attempts to calculate step lengths via approximating the curve of the step pattern with results deviating by 6-8% from results arrived at by empirical formulae. Further, this deviation is observed to reduce markedly with precise calibration and increase in regularity of steps, as seen in running or walking longer distances.

- Calibration is an essential part of the pedometer system: individual quirks, heel strike, significant body up-down movement and other factors all can and do affect the results obtained by the model. The calibrating factor is adjusted to offset the majority of these effects.

- 3-axis accelerometers are widely available on most electronic devices as IMEMS and are hence used as the basis of this model. The increasing prevalence of gyroscopes provides the opportunity for constructing a model based on more accurate readings of the mechanism of human walking.

Any human activity is uncertain and variable; we take an approach of constructing a model rooted in the physiology of human walking that can lead to a more realistic and efficient implementation of step and stride analysis in pedometers.

REFERENCES

[1] Diego Alvarez, Rafael C. Gonzalez, Antonio Lopez and Juan C. Alvarez, “Comparison of Step Length Estimators from Wearable Accelerometer Devices,” Proceedings of the 28th IEEE EMBS Annual International Conference, pp. 5964–5967, Aug-Sep 2006.

[2] J. W. Kim, H. J. Jang, D. H. Hwang and C. Park, "A Step, Stride and Heading Determination for the Pedestrian Navigation System"Journal of Global Positioning Systems (2004)Vol. 3, No. 1-2, pp. 273-279.

[3] S. Sakka, C. Hayot and P. Lacouture, "A generalized 3D inverted pendulum modelto represent human normal walking", IEEE/RSJ International Conference on Humanoid Robotics 2010.

[4] Q. Ladetto, V. Gabaglio, B. Merminod, P. Terrier and Y. Schutz, "Human Walking Analysis Assisted by DGPS".

[5] N. Zhao, "Full-Featured Pedometer Design Realized with 3-Axis Digital Accelerometer".

[6] T. M. Ahola, "Pedometer for Running Activity Using Accelerometer Sensors on the Wrist".