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A Gyroscope Based Accurate Pedometer Algorithm

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Abstract—**Accurate step counting is important in pedometer based indoor localization. Existing step detection techniques are not sufficiently accurate, especially at low walking speeds that are commonly observed when navigating unfamiliar environments. This is more critical when vision impaired indoor navigation is considered due to the fact that they have relatively low walking speeds. Almost all existing pedometer techniques use accelerometer data to identify steps, which is not very accurate at low walking speeds. This paper describes a gyroscope based pedometer algorithm implemented in a smartphone. The smartphone is placed in the pocket of the trouser, which is a usual carrying position of the mobile phone. The gyroscope sensor data is used for the identification of steps. The algorithm was designed to demand minimal computational resources so that it can be easily implemented in an embedded platform. Raw data from the sensor are filtered using a 6th order Butterworth filter for noise reduction. This is then sent though a zero crossing detector which identifies the steps. A minimum delay between two consecutive zero crossings was used to avoid fluctuations being counted and peak detection was used to validate steps. The algorithm has a calibration mode, in which the absolute minimum swing of data is learnt to set the threshold. This approach demonstrated accuracies above 96% even at slow walking speeds on flat land, above 95% when walking up/down hills and above 90% when going up/down stairs. This has supported the concept that the gyroscope can be used efficiently in step identification for indoor positioning and navigation systems.**

Index Terms—***pedometer algorithms; gyroscopic data; single-point sensors; step detection; localization and navigation; vision imapired navigation***

I. INTRODUCTION

Accurate step counting is a critical parameter in pedometer based indoor localization systems in improving their accuracy and reliability. Existing step detection techniques, both hardware and software, does not satisfactorily cater the accuracies demanded by localization systems especially at low walking speeds observed in natural walking [1]-[3]. Situation may be worse with vision impaired indoor navigation is considered, especially in an unfamiliar environment. Most of existing pedometers use accelerometer data in detecting steps and are based on threshold detecting [4], [5].

The pedometer algorithm discussed in this paper is based on the proposal of using gyroscopes in human gait identification for indoor localization that was proposed by Abhayasinghe and Murray [6]. This research is a part of an indoor navigation system for vision impaired people.

The performance of some existing pedometers are discussed in the "Background" section whereas the novel, gyroscope based pedometer algorithm and its performance are discussed in the "Step Detection Algorithm" section and "Experimental Results" section of this paper.

II. BACKGROUND

Jerome and Albright [1] have compared the performance of five commercially available talking pedometers with the involvement of 13 vision impaired adults and 10 senior adults, and observed that the step detection accuracy for all of them were poor ($41 - 67\%$) while walking on flat land and the situation was worse when ascending stairs ($9 - 28\%$) or descending stairs ($11 - 41\%$). Crouter et al. [2] have compared 10 commercially available electronic pedometers and confirmed that they underestimate steps in slow walking. Garcia et al. [3] have compared the performance of software pedometers and hardware pedometers and observed that both these types are comparable in all walking speeds and both types have demonstrated poor accurately in slow (58 to $98\,\text{steps}\cdot\text{min}^{-1}$) walking speeds: $20.5\% \pm 30\%$ for hardware pedometer and $10\% \pm 30\%$ for software pedometer.

Waqar et al. [4] have used an accelerometer based pedometer algorithm with fixed threshold in their indoor positioning system. They have reported a mean accuracy of 86.67% in their 6 trials of 40 steps each, with a minimum accuracy of 82.5% and a maximum of 95%. The median accuracy was 85%.

A Smartphone pedometer algorithm based on accelerometer is discussed by Oner et al. [5] and their algorithm demonstrated sufficient accuracies at walking speeds higher than 90 beats per second (bps), but its performance degrades as speeds fall below 90 bps. Their algorithm has over counted steps and the error was approximately 20% at 80 bps, 60% at 70 bps and 90% at 60 bps.

Lim et al. [7] have proposed a foot mounted gyroscope based pedometer, but the authors have not mentioned the accuracy of their system. Further, they use force sensitive resisters (FSR) to detect the toe and heel contacts, and hence the accuracy of step detection should be higher as they can easily detect the Initial Contact using the FSR.

Ayabe et al. [8] have examined the performance of some commercially available pedometers in stair climbing and bench

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stepping exercises and recorded that the pedometers could count steps with an error of $\pm 5\%$ at speeds of 80 to 120 steps·min^{-1}. However, the accuracy was poor for low step sizes and lower stepping rates ($> \pm 40\%$ at 40 steps·min^{-1}).

Most of the examples discussed here used accelerometer data to detect steps and they perform poorly at slow walking speeds. The main reasons for this poor performance at low speeds are the static value (gravitational acceleration) present in the accelerometer, slow response of accelerometer and that most of these algorithms cannot adopt their threshold levels to suit with the pace of walking. This raises the requirement of an accurate step detection technique at slow walking speeds.

III. Step Detection Algorithm

A. Introduction

The work presented in this paper is based on the proposal made in [6] that the gyroscopic data can be exclusively used for gait recognition in indoor navigation applications. The authors have proposed that the output of a single point gyroscope sensor located in the pants pocket gives sufficient information to track the movement of the thigh and hence detect the steps.

B. Relationship Between Gyroscopic Data and Movement of the Thigh

A stride cycle is measured from the Initial Contact of one heel to the next Initial Contact of the same heal [9]. At the Initial Contact, the deflection of the thigh in the forward direction is a maximum. Fig. 1 shows the orientation of the thigh computed using gyroscopic data and low-pass filtered (with a 6th order Butterworth low pass filter with cutoff frequency of 5 Hz) gyroscopic X axis reading. Initial Contact points and the stride cycle identified based on the orientation are marked on the graph. The initial orientation when the leg is at rest was calculated by fusing accelerometer and the compass data. For this computation, the static value of the gyroscopic data was removed by deducting the average.

It can be clearly seen that the filtered gyroscopic data is close to zero at the Initial Contact point of the particular leg and has a negative gradient. Hence, the period from one negative gradient zero crossing point to the next of the filtered gyroscope reading is a stride cycle as shown in the figure.

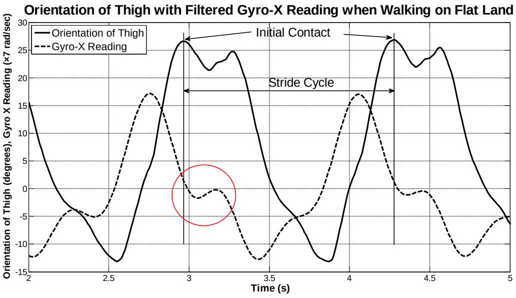

Figure 1. Orientation of the thigh with filtered gyroscope-X axis reading when walking on flat land

It was also observed that the negative gradient zero-crossing corresponds to the Initial Contact of that leg when walking on stairs and on an inclined plane too. Therefore it is clear that zero crossing detection of filtered gyroscopic data may be used in detecting the stride cycle, hence the steps, even if the person is walking on stairs or on an inclined surface.

In line with these observations, the device is assumed to be in vertical placement where forward and backward rotation of the thigh is read as gyroscopic X reading. Hence the real time processing is limited to gyro-X only.

C. Pre Processing of Data

Before attempting to identify zero crossings, the gyroscopic X axis data is filtered with a 6th order discrete Butterworth low-pass filter with cutoff frequency of 3 Hz. 3 Hz was selected as the cutoff frequency because the mean speed of fast gait is in the range of 2.5 steps per second [10]. The cutoff frequency was lowered as much as possible for better smoothness of the waveform so that the unwanted oscillations around zero are minimal, but still the stride cycle is visible in the waveform.

D. Zero-Crossing Detector

A simple 2-point zero-crossing detection was used to simplify the algorithm. Both positive and negative zero-crossings were detected by alternating the polarity of the zero-crossing detector because the positive zero-crossing corresponds to the starting point of Pre Swing of the particular leg, or the Initial Contact of the other leg. Hence, the total count of zero-crossings is the number of steps the person has walked.

E. Avoiding False Detections

As indicated by the circle in Fig. 1, the filtered gyroscopic signal may cross zero with a negative gradient for more than one time during the period from Initial Contact to Loading Response. However, because this period is between $0 - 10\%$ of the gait cycle [9] a timeout mechanism was used to avoid this unwanted zero-crossing being detected. Once a zero-crossing is detected, the zero-crossing detector remains disabled for 100 ms to avoid detecting these multiple zero crossings. 100 ms was selected as 15% of the stride cycle assuming a step frequency of 1.5 steps per second for slow gait [10]. This time delay is 30% of the stride cycle of average fast gait of 3 steps per second and hence it will not disturb the detection of the next zero-crossing of fast gait.

F. Validating the Detected Zero Crossings

A threshold detection mechanism was used in the algorithm to validate each zero-crossing detected. As shown in Fig. 1, the gyroscopic reading reaches the corresponding peak after the zero-crossing point. However, in the area marked by the circle, the relative maximum is well below the peak of the signal and that relative maximum does not correspond to the middle of the swing of a leg, hence need to be eliminated. The algorithm includes a calibration mode where the user has to walk with the slowest possible speed so that the smallest deflection of the gyroscope signal is learnt by the algorithm. After detecting a zero-crossing, the algorithm checks for the peak that follows the zero-crossing, and checks if it is larger than the threshold. The counter is incremented only if the peak is larger than the threshold.

G. *The Step Detection Algorithm*

A flow chart illustrating the step detection algorithm is depicted in Fig. 2. It should be noted that both positive and negative zero-crossings are detected by the algorithm and the polarity to be checked is toggled after each detection. However, the polarity toggling is not indicated in the figure to reduce graphical complexity.

H. *Implementation of the Algorithm*

The algorithm was implemented in Matlab® for simulation purposes and after confirming the outcomes of the algorithm using prerecorded data, it was implemented in an Apple iPhone 4S. During the implementation it was noticed that the algorithm could count the movements of the phone while in the hand, when placing the phone in the pocket before the trial and taking out of the pocket after the trial. Because Apple license does not allow use of some phone features [11], such as ambient light sensor to detect placement in the pocket, a time out mechanism and a manual correction was used at the beginning and at the end of the trial respectively. After pressing the start button, the application allows a timeout to allow user to place the phone in the pocket. The algorithm starts detecting steps only after the timer has timed out. Manual decrement of the total count by one was done to compensate the false count at the end when the phone is taken out of the pocket.

IV. EXPERIMENTAL RESULTS

The simulations indicated that the accuracy of step counting of the algorithm on prerecorded data was 100%. The algorithm was tested in the real world for five different activities: walking on flat land, upstairs, downstairs, uphill and downhill, with the involvement of 5 male and 5 female volunteers. They were asked to place the phone vertically in the pants pocket and perform the relevant activity. The tests were conducted in two stages: first with normal walking speed and then with five different stepping rates (50, 75, 100, 125 and 150 steps·min^{-1}). The actual number of steps that the subject traveled was counted for each trail by a note taker.

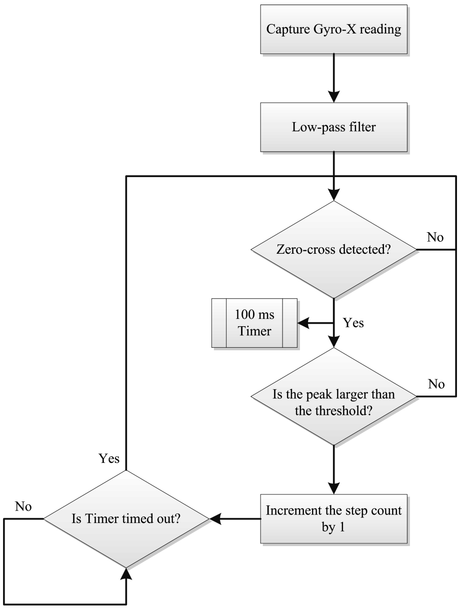

Figure 2. Flow Chart of the Step Detection Algorithm

Table I shows sample results of a single subject performing different activities with normal stepping rate. In that set of trials, the algorithm showed above 95% accuracy in every activity.

Table II shows statistics of actual number of steps, number of steps counted by the algorithm and the accuracy in all trials. It can be seen that the algorithm has shown a minimum mean accuracy of 94.55% for going downstairs and the minimum reported accuracy for all the trials of 90.91% for stair climbing (both up and down). However, the minimum accuracy reported by the algorithm for walking on flat land is 96.00% with a maximum of 100%. The algorithm has reported accuracies greater than 95% for walking on an inclined surface with a mean accuracy of 97.17% for going down and 98.18% for going up.

The second set of experiments were conducted for walking on flat land and on stairs only, where the subjects were asked to walk with five stepping rates: 50, 75, 100, 125 and 150 steps·min^{-1}. For walking on flat land, the minimum accuracy of 94.59% was reported at 75 steps·min^{-1} whereas the mean accuracy for that speed was 97.89%. The statistics are shown in Table III. However, the minimum accuracy reported at 50 steps·min^{-1} was 96% and the accuracy was greater than 96% at all other stepping speeds.

The minimum accuracy reported in going up stairs and down stairs was 90.91% where the total number of steps considered in each case was 11. Although this is the absolute minimum, the lowest mean accuracy reported when walking up stairs was 96.36% and that is at 75 and 125 steps·min^{-1}. For walking down stairs, the lowest mean accuracy reported was 95.45% for the stepping speeds of 50 and 125 steps·min^{-1}.

V. DISCUSSION AND FUTURE WORK

Trials of walking on stairs had to be limited to 11 steps per trial due to unavailability of long stairways. Due to this reason,

Table I
SAMPLE RESULTS OF ONE SUBJECT

Activity	**Actual No. of Steps**	**Steps Counted by Algorithm**	**Accuracy (%)**
Walking slowly on flat land	27	26	96.30
Walking faster on flat land	49	49	100.00
Walking up stairs	11	11	100.00
Walking down stairs	11	11	100.00
Walking up hills	40	40	100.00
Walking down hills	43	41	95.35

Table II
STATISTICS OF THE PERFORMANCE OF THE ALGORITHM FOR DIFFERENT ACTIVITIES

Activity	**Actual No. of Steps**		**Steps Counted by Algorithm**		**Accuracy (%)**			
	Mean	*Var*	*Mean*	*Var*	*Mean*	*Var*	*Min*	*Max*
Walking slowly on flat lands (<60 steps·min^{-1})	28.50	2.45	27.60	2.64	96.82	1.16	96.00	100.00
Walking faster on flat lands (>100 steps·min^{-1})	49.10	1.29	48.50	0.65	98.80	1.73	96.08	100.00
Climbing up stairs	11.00	0.00	10.70	0.21	97.27	17.36	90.91	100.00
Climbing down stairs	11.00	0.00	10.40	0.24	94.55	19.83	90.91	100.00
Walking on inclined plane(up)	43.30	2.01	42.50	1.45	98.18	1.87	95.45	100.00
Walking on inclined planes(down)	42.20	1.36	41.00	1.20	97.17	2.02	95.24	100.00

Table III
STATISTICS OF THE PERFORMANCE OF THE ALGORITHM FOR WALKING ON FLAT LAND WITH DIFFERENT STEPPING RATES

Activity	**Actual No. of Steps**		**Steps Counted by Algorithm**		**Accuracy (%)**			
	Mean	*Var*	*Mean*	*Var*	*Mean*	*Var*	*Min*	*Max*
50 steps·min^{-1}	25.90	1.09	25.50	0.85	98.49	3.43	96.00	100.00
75 steps·min^{-1}	37.80	0.96	37.00	1.20	97.89	2.58	94.59	100.00
100 steps·min^{-1}	51.00	1.00	49.90	1.29	97.85	1.89	96.00	100.00
125 steps·min^{-1}	62.50	0.65	62.00	0.40	99.21	0.63	98.39	100.00
150 steps·min^{-1}	74.50	0.65	73.90	1.69	98.92	0.66	97.26	100.00

the false count at the end of the trail is large as a percentage to the total number of steps. This is the main reason for low accuracy. Although the number of steps will be less in real application too, the phone will not be taken out of the pocket by the end of the stair case and hence the aforementioned error count will not occur. In addition to that, the vendor restrictions have restricted us using some facilities of the phone to detect whether the phone is in the pocket. This reason has caused the accuracy of the algorithm for other activities also to drop below 100%.

Implementing the algorithm in other platforms will be the next step to see the real performance of the algorithm with all features. The algorithm discussed in this paper assumes defined and fixed orientation of the phone in the pants pocket. Currently the authors are working on improving the algorithm so that it can be used with different orientations in the pocket. The focus is to include an orientation correction into the algorithm such that the correct gyroscopic axis or combination of axes is used. However, the placement is still limited to the pants pocket as the authors have identified the pants pocket as the most suitable place for device placement for step detection [6].

VI. CONCLUSIONS

This paper presented a single-point gyroscope based pedometer implemented in a Smartphone as a component in the development of an indoor way finding system for people with vision impairment. From the testing conducted for different activities and different stepping speeds, the algorithm gave promising results and high step detection accuracy even at low walking speeds. The gyroscope based step detection can be easily used as an accurate step counting technique for indoor localization and navigation systems not only on level terrain, but also on tilted terrains and on stairs.

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