Accurate Pedometer for Smartphones

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***Abstract*—Accuracy of step counting is one of the main problems that exist in current Pedometers, especially when walking slowly on flat lands and performing different activities, such as climbing up and down stairs and walking on inclined planes. Although accelerometer based pedometers provide a reasonable accuracy when walking at higher speeds, the accuracy of them are not sufficient at slow walking speeds and performing different activities. This paper proposes a novel algorithm to detect steps using single-point gyroscopic sensors embedded in mobile devices. Preliminary analysis of data collected in different environments with the involvement of male and female volunteers indicated that gyroscope alone provides sufficient information necessary for accurate step detection. Algorithm was developed based on the gyroscopic data in conjunction with zero crossing and threshold detection techniques. The results proved that gyroscope based step detection algorithm provide a high accuracy when performing different activities and at slow paced walking.**

***Index Terms*—Pedometer algorithms; gyroscopic data; single-point sensors; off-the-shelf devices; mobile applications**

I. Introduction

Modern medical researches highlight that pedometers support not only to physical body but mental activities of human beings to a greater extent [1], [2], [3]. Low cost pedometers help to improve the motivation of the walker [4], indoor navigation, activity recognition and for various applications in the field of health care. Pedometers can be used to detect steps from vertical acceleration of the human body. This works under two systems of mechanism. One is of mechanical based and other being of the electrical based accelerometers. Modern pedometers are generally based on MEMS (micro-electromechanical systems) accelerometer, mostly 1–axis, but the use of 2–axis and 3–axis accelerometers and gyroscopes improves the precision and releases some utilization constraints e.g. positioning of the pedometer. The accuracy of these systems is at an acceptable level but not perfect due to various drawbacks [5]. Applications of pedometer are now upgraded and can be found in mobile devices. It is obvious with the application of pedometers to mobile devices, has now improved the standards of healthcare applications.

This paper describes a gyroscope data based pedometer implemented in an Apple iPhone. The work and results presented in this paper is an extension to the work presented in [6] by the authors. The approaches of some pedometer algorithms proposed by researchers are discussed in the "Background" section including their features and drawbacks, and the novel algorithm is explained in the "Implemented Algorithm" section while its performance and future work are discussed in "Experimental Test and Result" and "Discussion and Future Work" sections.

II. Background

Crouter et al. [7] have compared the accuracy and reliability of 10 pedometers available in the market. These pedometers were based on mechanisms like, accelerometer, metal-on-metal and magnetic reed proximity switch. It is important to notice that all the testing was done at normal walking speeds. Their conclusion was that accuracy of pedometers was highly subjective upon the internal mechanism and sensitivity. But they have failed to measure the accuracy of pedometers when walking slowly and performing different activities like ascending and descending stairs.

A comparative study with commercially available pedometers done by Jerome and Albright [8] has shown that the accuracies are poor with a minimum average absolute error value of 13%. Their conclusion was that none of the pedometers can be used for research purpose or general usage.

Waqar et al. [9] have developed a pedometer based on accelerometer for their indoor positioning system which consists of a preset threshold based peak detection method to identify a valid step and step cycle pattern detection method to discard invalid steps due to instantaneous readings of the accelerometer. It should be noted that the results of the pedometer may change with different individual walking patterns and speeds due to preset threshold. 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%.

Oner et al. [10] have implemented another step detecting algorithm for their "Early detection of the falling event system". Step detection of this particular algorithm relies on the detecting peaks within a period in the data produced by the accelerometer sensor during walking. They were able to achieve higher accuracies during higher speeds (90 beats per second (bps)) of walking and with the mobile based pedometer placed fixed and loose in the pocket. However, their algorithms failed to count steps accurately during slow paced walking. Their algorithm has over counted steps and the error was approximately 20% at 80 bps, 60% at 70 bps and 90% at 60 bps.

Lee et al. [11] were able to achieve 99% accuracy in their portable acceleration sensor module with some advanced processing like FFT, Fuzzy C and statistical calculations. But they have agreed finally that their system does not process data in real time, inability to measure steps during activities like ascending and descending stairs walking and need for an efficient device to carry out processing.

Cavalcante et al. [12] have developed a pedometer to be used with their research on "Real-time indoor tracking on mobile devices". System compares mean values of acceleration samples in conjunction with a sliding window mechanism to detect steps. Their conclusion was that a proper sampling rate, sliding window and quality sensors embedded in mobile devices are a major requirement to detect steps accurately. However, they have not mentioned the exact accuracy of their system.

According to the comparative study on the accuracies of mobile phone based pedometers with the commercially available pedometers conducted by Garcia et al. [4], the mobile phones provide a competitive performance against the commercially available pedometers. Further both indicate less accuracy when at slower speed and high accuracy while in faster walking.

Lim et al. [13] 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.

Zhong et al. [14] have proposed an accelerometer based step detection algorithm that involved an adaptive threshold technique. Although they could achieve accuracies above 90%, they also involve sensors attached onto the body. Attaching sensors may not be a problem in laboratory conditions, but for a commercial system, body mounted sensors is not convenient for the user. This should be considered seriously in the case of vision impaired users as we should not request them to attach many sensors onto the body.

A comparative study on the accuracies of mobile phone based pedometer technologies by Boyce et al. [15] concluded that mobile phone based applications lag behind the use of a commercially available pedometer when determining step count. Further manipulation of settings is required to improve the accuracy of step counting for one activity level, but recalibration is required as intensity of activity changes.

M. Ayabe et al. [16] have examined the performance of some commercially available pedometers in stair climbing and bench stepping exercises and recorded that the pedometers could count steps with an error of $\pm 5\%$ at speeds of 80 to 120 steps$\cdot$min^{-1}. However, the accuracy was poor for low step sizes and lower stepping rates ($> \pm 40\%$ at 40 steps$\cdot$min^{-1}).

Most of the previous research have identified that pedometers are less valid and reliable during 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. Implemented Algorithm

A. Introduction

The algorithm presented in this paper is based on the proposal made in [17] 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. This algorithm uses gyroscopic data only to predict steps. Details of the algorithm are discussed in the following sections.

B. Initial Concept Behind the Algorithm

As presented in [6], the leg movement during walking shows a sinusoidal like behavior. This behavior can be clearly identified by monitoring the angular velocity of the leg. Therefore one axis of the gyroscope provides the information about the movement of the leg depending on the orientation of the device. A small research on "ways of placing the modern mobile devices on a pocket" proved that almost all the users placed their devices vertically in the pocket. Therefore monitoring the gyroscopic x axis data is considered. It is important to notice for different orientations only variable that needed to change is the axis that we are obtaining data from the gyroscope. The plot of the orientation of the thigh and the filtered gyroscopic data indicate that there is a close relationship between these two [18]. Fig. 1 shows the orientation of the thigh computed using gyroscopic data and the filtered (with a 6$^{\text{th}}$ order Butterworth low pass filter with cutoff frequency of 5 Hz) gyroscopic x–axis data. It indicates that the Initial Contact point of the leg can be clearly identified and the negative zero crossing of the gyroscopic signal corresponds to the Initial Contact. Further, this behavior was observed when climbing stairs and walking on inclined plane which are depicted in Fig. 2 and Fig. 3.

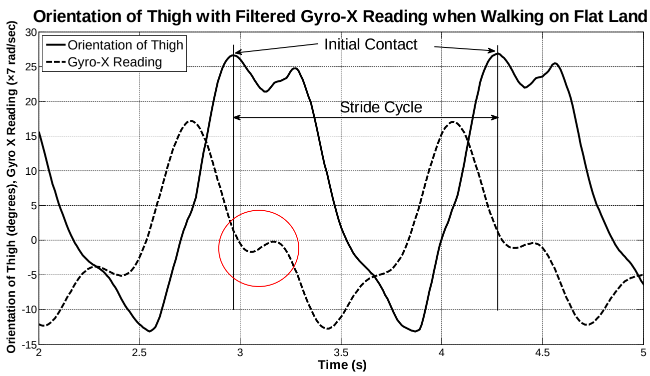

Figure 1. Orientation of the thigh with filtered gyroscope-X axis reading when walking on flat land [18]

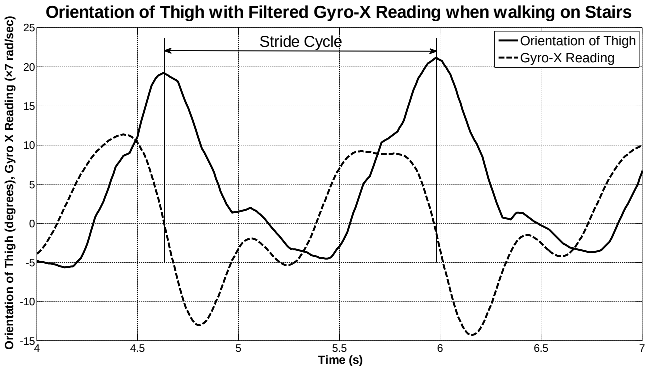

Figure 2. Orientation of the thigh with filtered gyroscope-X axis reading when walking on stairs

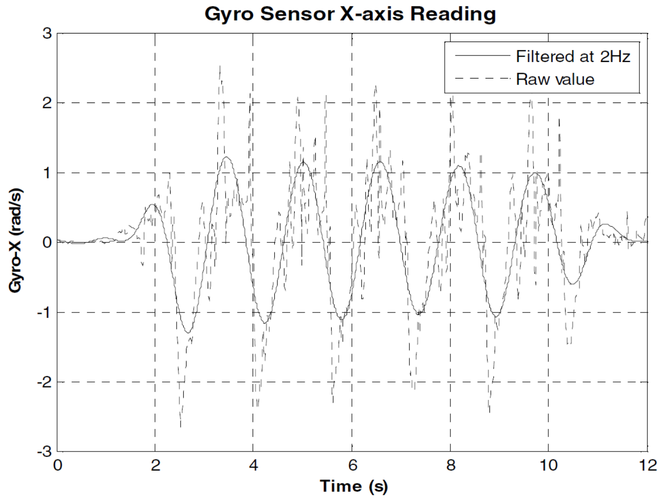

Figure 4. Gyroscopic X axis reading (raw and filtered at 2 Hz) [6]

C. Filtering of Raw Data

Initially raw data are filtered using a proper filter that would preserve the properties of walking. A typical walking speeds are in the range of 1.5 steps per second (for slow walking) to 3 steps per second (for fast walking) [19]. A choice of cutoff frequency that accommodates slow-paced activities is a major concern in achieving better accuracy. Therefore choice of the filter was a simple 6th order Butterworth low-pass filter having a cutoff frequency in the range of 0.9 Hz to 3 Hz. Fig. 4 depicts the raw gyro-x value and filtered version (at 2 Hz) of it.

D. Removal of Unwanted Signal Components

Gyroscopic data takes a sinusoidal behavior after filtering for both steps and instantaneous movement of the device. A sample out technique is used to reduce false counts due to instantaneous movement of the device. According to the experimental results a step occurs on an average of 0.40 to 1.20 seconds depending on the intensity of walking. Therefore once a step is detected, the algorithm is set to eliminate any signal that can be counted as a valid step before the average step time. 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 [19]. 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.

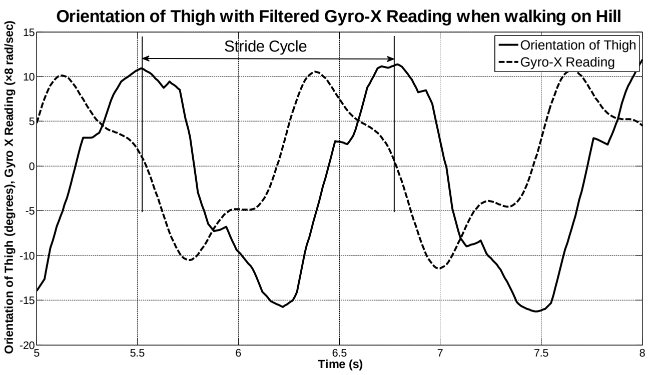

Figure 3. Orientation of the thigh with filtered gyroscope-X axis reading when walking on an inclined plane

E. Identification of Key Features of the Filtered Signal

The main idea for the step detection in this algorithm relies on detecting zero crosses of filtered gyro–x. Fig. 5 illustrates the consecutive zero crosses that occurs during a two consecutive stride cycles. In addition to zero crossing detection, an adaptive peak threshold is used to validate a step. An individual can train the algorithm to learn the minimum possible signal peak that can be used to validate a step, especially when walking as slowly as possible and descending stairs. If the signal does not cross the threshold after a zero-cross, a step will not be counted. Threshold peak detection helps to avoid instantaneous and small

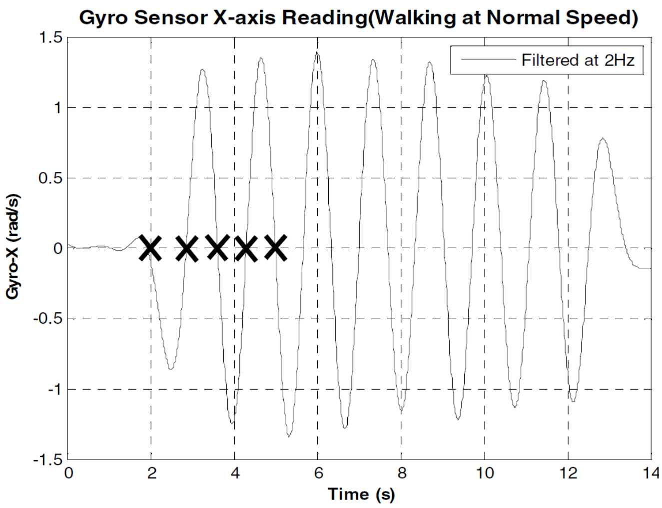

Figure 5. Strength of the gyro-x signal when walking at a medium pace [6]

movements of the device. Further this threshold peak can be adjusted so that the algorithm is capable of detecting steps when the device is placed in different pockets which are loose or tight (signal strength differs with the environment where the device is placed). Fig. 5, Fig 6 and Fig 7 depict the strength of the gyro-x signal (upward-peak signal) when walking (Average = $1.3\,\text{rad}\cdot\text{s}^{-1}$), ascending (average = $1.6\,\text{rad}\cdot\text{s}^{-1}$) and descending (average = $0.9\,\text{rad}\cdot\text{s}^{-1}$) stairs for an individual. It is important to note that these averages vary with different patterns and intensities of walking.

F. Implementation of the Algorithm

A flow chart illustrating the step detection algorithm is depicted in Fig. 8. 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.

The algorithm was implemented in Matlab® for simulation purposes before the real implementation. During simulation it was observed that there is a delay introduced by the filter when the recurrent equations are used for the filter. However, that delay does not affect the performance of the algorithm as there is no need of synchronizing multiple sensor data due to the fact that only gyroscopic-X reading in analyzed in the algorithm.

After confirming the outcomes of the algorithm using prerecorded data, the algorithm was implemented in an Apple iPhone 4S and iPod 4G. A screenshot of the application developed in iPhone is shown in Fig. 9. 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 [20], 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 Test and Result

Testing of the algorithm was done with the involvement of 5 male and 5 female members with random heights and weights. Since this algorithm aimed to detect steps irrespective of age, sex and various physical aspect of human being, we were not much concerned of varieties of the people involved, their sex etc. The vertical position is considered as zero degrees orientation. The participants were instructed to perform different activities, such as climbing up and down stairs and walking on inclined planes. A sample of counted steps for an individual is tabulated in Table I. In that set of trials, the algorithm showed above 95% accuracy in every activity.

A Similar reading profile was maintained for each individual who participate the testing process. Statistics of all walking trials are tabulated in Table II. 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 $\text{steps}\cdot\text{min}^{-1}$. For walking on flat land, the minimum accuracy of 94.59% was reported at 75 $\text{steps}\cdot\text{min}^{-1}$ whereas the mean accuracy for that speed was 97.89%. The statistics are shown

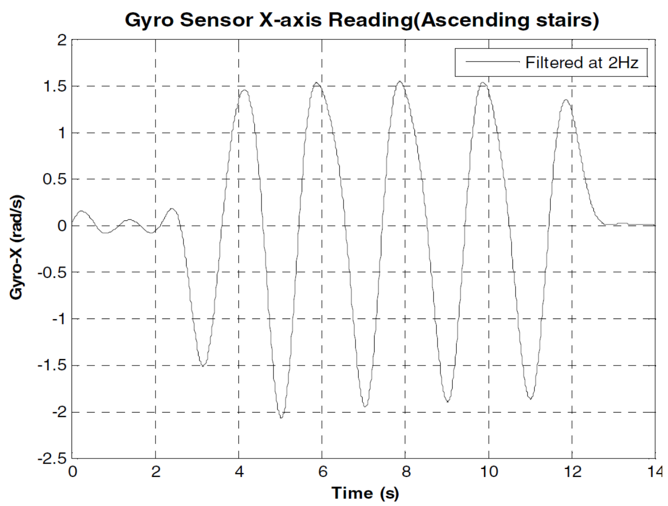

Figure 6. Strength of the gyro-x signal when ascending stairs[6]

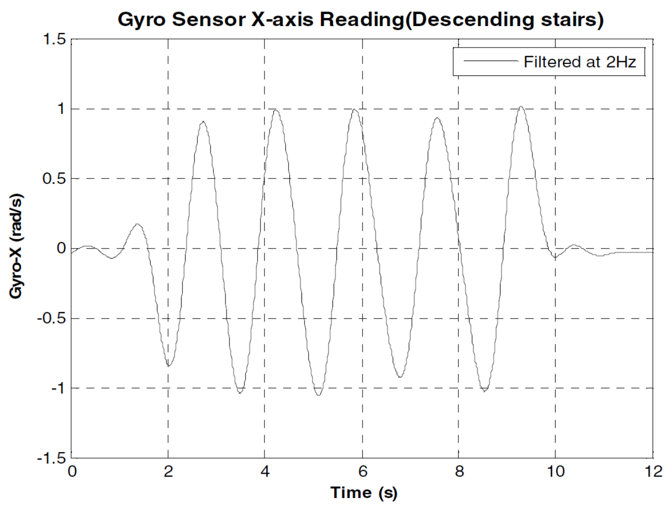

Figure 7. Strength of the gyro-x signal when descending stairs [6]

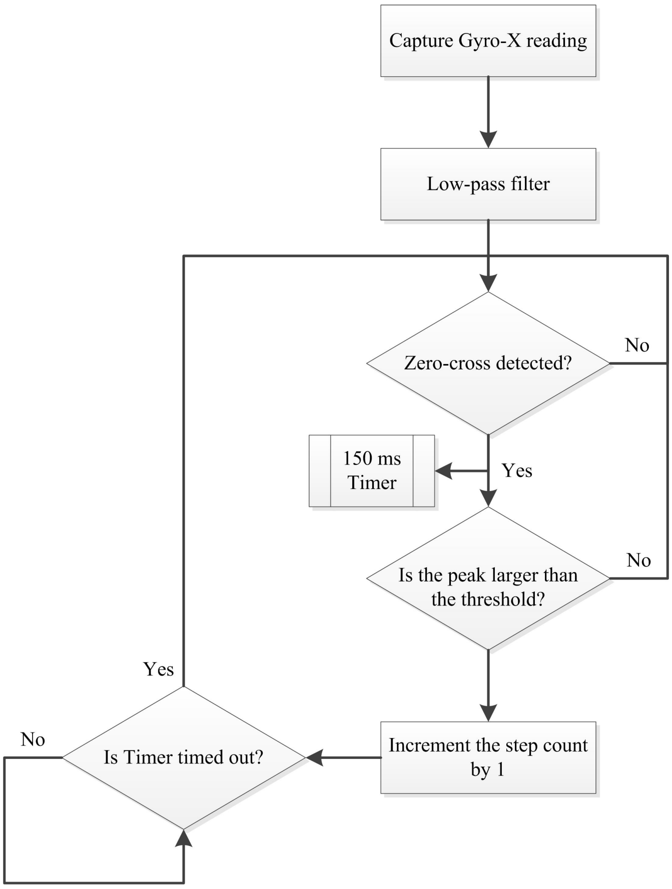

Figure 8. Flow Chart of the Step Detection Algorithm [18]

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%

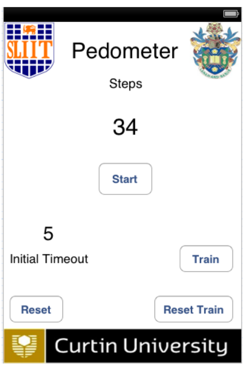

Figure 9. Screenshot of the iPhone Application

Table I
SAMPLE RESULTS OF ONE SUBJECT PERFORMING DIFFERENT ACTIVITIES[18]

Activity	**Actual No. of Steps**	**No. of 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

for the stepping speeds of 50 and 125 steps·min^{-1}. Statistics of walking trials on stairs are shown in Table IV and Table V.

Overall accuracy of the algorithm was above 94%. It is evident from the results that climbing down stairs registered a low percentage of accuracy. This is mainly due to the weak signal strength by the user. Apart from that other errors were due to weak signal strength of different individuals at the start and end of the travel.

V. DISCUSSION AND FUTURE WORK

There are several advantages in gyroscopic data based step detection algorithm. One main advantage is the ability to detect steps at slow speeds for both walking and stepping up and down. This is achieved by setting a proper filtering process along with an adaptive peak threshold set by the user. It is important to notice that accuracies of pedometers at slow speeds of activity intensities were a major requirement for both research activities and consumers of pedometers.

In addition to those, the algorithm depends only on the data of a single axis of the gyroscope. This provides lesser computations and ability to integrate this function in research areas like Indoor Navigation.

Further algorithm is implemented in currently available high end mobile devices, which is more convenient to be used with any application as sensors are not attached to the body.

Although walking trails, both on flat land and on inclined land, could be conducted with sufficiently large number of steps per trial, due to unavailability of long stairways, trials of walking on stairs had to be limited to 11 steps per trial. Due to this reason, the false count at the end of the trail (when taking the phone out of the pocket) is large as a percentage to the total number of steps. This is the main reason for the accuracy to become as low as 90%. 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%. However, even with this problem, the accuracy remains more than 96% even at low stepping speeds (<60 steps·min^{-1}). The minimum accuracy was

Table II

STATISTICS OF THE PERFORMANCE OF THE ALGORITHM FOR DIFFERENT ACTIVITIES

Activity	**Actual No. of Steps**		**No. of 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**		**No. of 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

Table IV

STATISTICS OF THE PERFORMANCE OF THE ALGORITHM FOR WALKING UP STAIRS WITH DIFFERENT STEPPING RATES

Activity	**Actual No. of Steps**		**No. of Steps Counted by Algorithm**		**Accuracy (%)**			
	Mean	***Var***	***Mean***	***Var***	***Mean***	***Var***	***Min***	***Max***
50 steps·min^{-1}	11.00	0.00	10.80	0.16	98.18	13.22	90.91	100.00
75 steps·min^{-1}	11.00	0.00	10.60	0.24	96.36	19.83	90.91	100.00
100 steps·min^{-1}	11.00	0.00	10.80	0.16	98.18	13.22	90.91	100.00
125 steps·min^{-1}	11.00	0.00	10.60	0.24	96.36	19.83	90.91	100.00
150 steps·min^{-1}	11.00	0.00	10.90	0.09	99.09	7.44	90.91	100.00

a little less in the case of walking on inclined land, but still was larger than 95%.

During the trials conducted with different stepping speeds too, the same issue has lowered the accuracies reported. The minimum accuracy reported at all speeds on stairs (both going up and down) was 90.91% and was because of the fact that the total number of steps per trial was 11. The minimum accuracy reported on flat land with different speeds was either close to or greater than 95%. In this case too, the false count at the end was a main reason for this accuracy drop.

As the restrictions of Apple license has limited the usage of features, implementing the algorithm in other platforms will be the next step to see the real performance of the algorithm will 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 [17].

Further, integrating an activity recognition algorithm with the proposed algorithm may increase the accuracy during different activities.

VI. Conclusions

This paper presented a single-point gyroscope based pedometer implemented in a Smartphone. 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. Overall accuracy of the algorithm was above 94%, with remarkably high accuracies at even slow walking speeds. It is also important to note that this accuracy can be further improved with proposed engineering techniques. It is confirmed that 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.

Table V
STATISTICS OF THE PERFORMANCE OF THE ALGORITHM FOR WALKING DOWN STAIRS WITH DIFFERENT STEPPING RATES

Activity	**Actual No. of Steps**		**No. of Steps Counted by Algorithm**		**Accuracy (%)**			
	Mean	***STD***	***Mean***	***STD***	***Mean***	***STD***	***Min***	***Max***
50 steps·min^{-1}	11.00	0.00	10.50	0.25	95.45	20.66	90.91	100.00
75 steps·min^{-1}	11.00	0.00	10.70	0.21	97.27	17.36	90.91	100.00
100 steps·min^{-1}	11.00	0.00	10.60	0.24	96.36	19.83	90.91	100.00
125 steps·min^{-1}	11.00	0.00	10.50	0.25	95.45	20.66	90.91	100.00
150 steps·min^{-1}	11.00	0.00	10.80	0.16	98.18	13.22	90.91	100.00

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