Low Power Shoe Integrated Intelligent Wireless Gait Measurement System

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Abstract. Gait analysis measurement is a method to assess and identify gait events and the measurements of dynamic, motion and pressure parameters involving the lowest part of the body. This significant analysis is widely used in sports, rehabilitation as well as other health diagnostic towards improving the quality of life. This paper presents a new system empowered by Inertia Measurement Unit (IMU), ultrasonic sensors, piezoceramic sensors array, XBee wireless modules and Arduino processing unit. This research focuses on the design and development of a low power ultra-portable shoe integrated wireless intelligent gait measurement using MEMS and recent microelectronic devices for foot clearance, orientation, error correction, gait events and pressure measurement system. It is developed to be cheap, low power, wireless, real time and suitable for real life in-door and out-door environment.

1. Introduction

This paper proposed a complete system called i-SMART ShoE II, a newer version to i-SMART Shoe. The i-SMART SHoE II focuses on both foot clearance measurement and orientation of the swing phase and also plantar pressure measurement during stance phase. The foot clearance measurement is the measurement of the distance between foot or shoe bottom and ground. This system is the combination of the ultrasonic sensor readings and the inertial measurement unit sensor. The ultrasonic sensor is used for direct clearance measurement and the inertial measurement unit sensor is used for orientation measurement. Based on the orientation measurement, the clearance measurement is corrected by an algorithm processing by microcontroller. The correction is required due to the orientation of foot during swing phase, landing phase, and toe off phase. In those situations, the positioning of ultrasonic on the back of the shoes may cause its orientation to be not perpendicular to the ground. So, an algorithm is required to recalculate and correct the data so as to represent the real and accurate data. Besides that, the characterization of a low cost piezoceramic device is performed so as to evaluate its capability in capturing foot plantar pressure as an insole embedded pressure sensor array. The insole is to be inserted into the shoes so that it can record plantar pressure when the subject is walking, running or standing. This capability makes it to be able to produce the foot pressure mapping for biometric application and early stage of diabetic detection.

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2. Experimental setup and Hardware Description

Figure 1 illustrates a block diagram of the i-SMART SHoE II prototype system. The system design is a stand-alone system consisting of six parts which are Inertia Measurement Unit (IMU), ultrasonic sensor, ceramic based piezoelectric sensor (piezoceramic sensor), radio transmitters and receivers (XBee modules produced by Digi International Inc., USA), Arduino processing unit and personal computer software. The piezo pressure sensor array is used to obtain the pressure map under the sole. Ultrasonic and IMU sensor operated as orientation and distance measurement parts. The sensors are attached to the data acquisition system via Xbee transmitter and receiver while the data acquisition system at microcontroller will be connected to the PC via a USB interface.
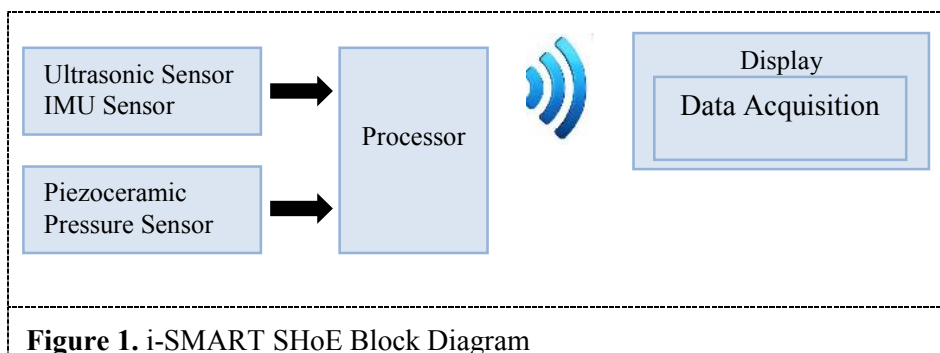
Figure 1. i-SMART SHoE Block Diagram

*2.1 Foot Clearance and Orientation Measurement Requirement*

Foot clearance is a critical parameter is identifying and prevention risk of falls among the elderly. It is also important for rehabilitation monitoring and sports training. The measurement should be done in real life activities to ensure the study of foot clearance is accurate and real. It is necessary to attach the sensor to shoe without interfering the subject's movement. The sensor should have the ability to measure clearance of both feet as explained in [1-4]. In order to have such ability, the sensor should be small and as light as possible with weight under 300 g as stated in [5]. Study in [6] suggests the closest maximum range for toe clearance of up to 20 cm is preferred. The study in [6] also suggests minimum foot clearance during the swing phase of walking to be within 3 cm above the walking surface. For sports application, this range will be significantly more [7]. The selections of sensors and hardware are depending on the requirement of the foot clearance and orientation measurement. The sensors that are used in this research are ultrasonic sensor and IMU for determination of the foot clearance as well as the orientation of foot position respectively. The monitoring system is not complete without other additional components that support the key functionality of the entire system. The hardware design consists of Arduino microcontroller, 2.4 GHz IEEE 802.15.4 XBee transceiver and power supply unit. Figure 2 shows the attachment unit for foot clearance and orientation measurement system.
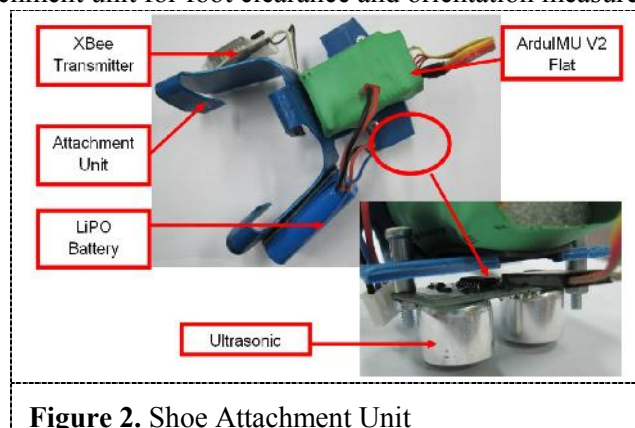
Figure 2. Shoe Attachment Unit

2.3 Insole Pressure Sensor

In our previous research as reported in [1], a MEMS pressure sensor for foot plantar pressure measurement was completed. However, in this work, we are trying a new cheaper and lower power device based on piezoelectric sensing. The piezoceramic pressure sensors as discussed below are originally the part of a cheap buzzer. It is taken out of the buzzer package carefully and repackaged with wires in an insole at three difference pressure points. These highly ruggedized sensors are being connected to XBee transmitter. The electronic board for RF reception is attached to a computer using USB connectivity and the computer placed nearby within certain range with the shoes integrated wireless acquisition board. In the computer, Arduino software has been used for the analysis of the wirelessly transmitted foot pressure and movement pattern readings.
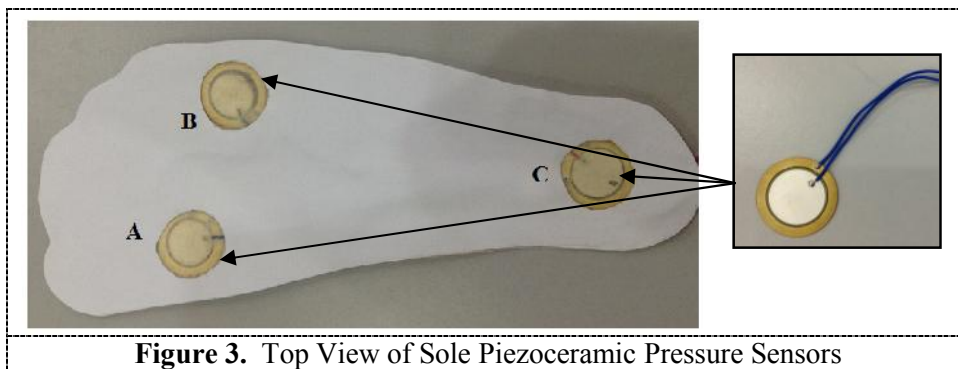
Figure 3. Top View of Sole Piezoceramic Pressure Sensors

Voltage to pressure converter forms the heart of this system. Voltage induced by the pressure of the foot plantar points is the key raw data. It is related to the mass (m) of its equivalent pressure unit either in N/m^2, Pa or Psi. The converter consists of a basic force formula with respect to the piezoceramic sensing area, *A*. The total force can be calculated from the output data using the equation (1) and (2). The equivalent value for pressure unit is shown in Table 1.

$$F = ma \tag{1}$$

$$P = \frac{F}{A} \tag{2}$$

Table 1. Equivalent Value for Pressure Unit

N/m^2	Parameter
1.0	1 Pa
1.0	0.0001450377 Psi

2.4 Power System

Based on the foot clearance, orientation and pressure measurement requirement, the real life measurement can be realized by wirelessly. For i-SMART SHoE II design, the system is powered up by a Lithium Polymer battery. It is a rechargeable battery and can be used up to 4 hours. Based on the limitation of battery lifetime, this paper comes out with the idea to reduce overal power consumption by turning on and off the different units beginning and ending at certain events.

2.5 Uniqueness of this work

The human gait consists of two phases namely stance phase, which is the period when the foot is on the ground, and the swing phase that corresponds to the period the foot is swung above the ground. By measuring the parameters during these two phases, a complete gait analysis measurement can be achieved. As explained in the subsections above, this work is unique as it integrates both foot plantar pressure measurements and foot clearance together in a new system, enabling both gait phases to be measured. Moreover, it innovatively uses very low cost piezoelectric sensors for pressure and event sensing. In addition, this work also enables intelligent system power control based on gait phase that saves electrical power usage of the system. For diabetic ulceration, pressure is the indicator. Therefore, by being able to detect the pressure beneath the foot especially at a number of points, possibility of ulceration can be detected and thus corrective measures can be implemented. This way the developed system may help the communities such as athletes, the elderly, patients undergoing rehabilitation, those diagnosed with diabetes and many more.

3. Experimental Result

The i-SMART SHoE II is a complete attachment unit with custom designed software for foot clearance measurement system. The total weight of attachment unit is about 115g. So, the weight of attachment unit fulfills the weight requirement of attachment unit which is less than 300g [5,7].

3.1 Ultrasonic and IMU System Evaluation

The testing is performed involving few subjects by attaching the attachment unit on their shoes and allow them to walk naturally in the outdoor. Figure 4 shows the gait pattern for walking subject using combination of ultrasonic sensor and IMU sensor. For this system, the data collected is more detail compared to the previous system. The system will analyzed the gait pattern based on foot clearance that classified to gender, feet, age range, toe off phase, maximum foot clearance phase and landing phase. The system is fixed on the attachment unit and attached to the subject shoes. The subjects need to walk as their daily activity. To ensure this system can be used in real life, this experiment is conducted out of laboratory. In this version, the error correction features is implemented where the error correction features is the new approach for foot clearance measurement which is being the novelty of this research.
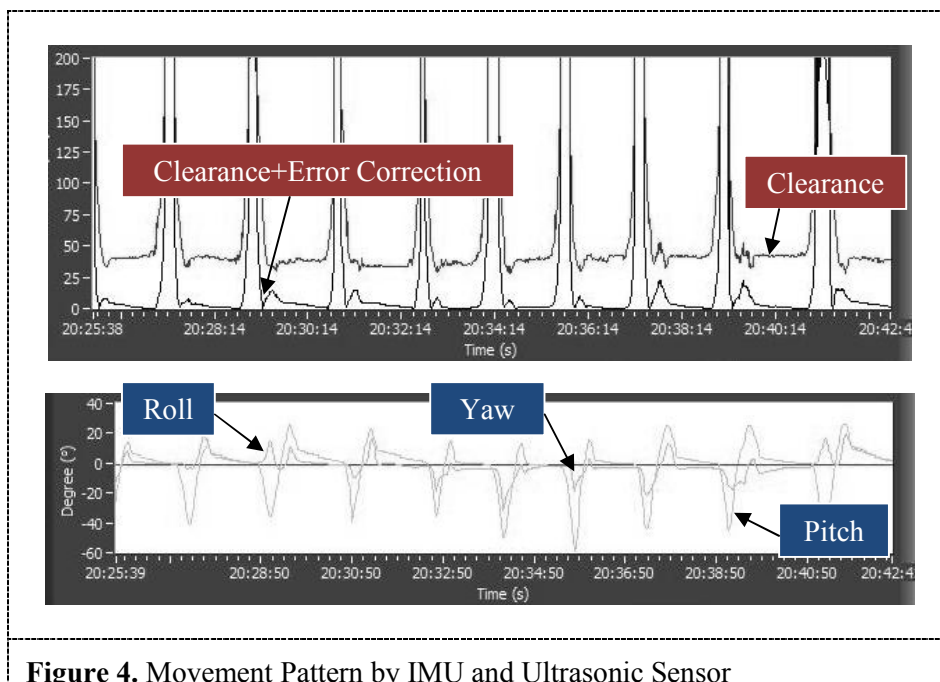

Figure 4. Movement Pattern by IMU and Ultrasonic Sensor

3.2 Pressure Test Bench

The piezoceramic sensors developed was tested in a custom made test bench with varying loads for calibration and to identify sensor linearity and response. The system is also evaluated during real walk and run activities to further characterize the system. Sensors are calibrated under linearly varying weight by the custom made test bench. The changes in output values with different loads applied and voltage generated is monitored. Voltage generated is found to vary proportionally with the applied load. Pressure is applied uniformly on the piezoceramic disk causing the piezoelectric effect to be generated. The experimental result is shown in Table 2.
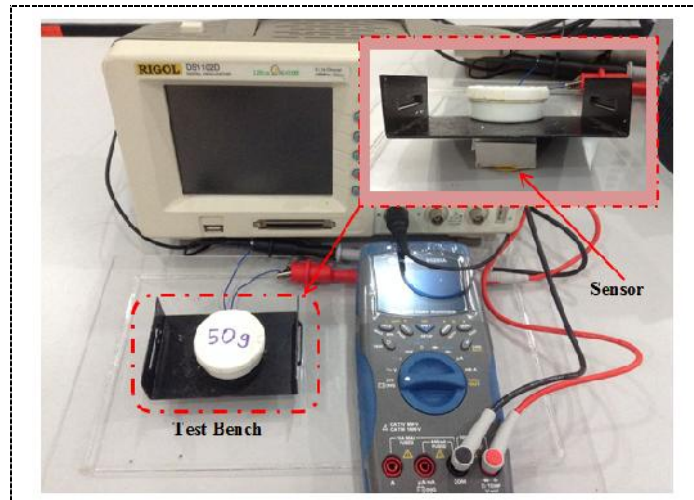
Figure 5. Calibration Procedure Undertaken by Custom Made Test Bench

Table 2. Voltage generated by applied force.

Mass (kg)	Voltage (V)
0.5	2.749
1.0	6.335
1.5	8.129
5.5	18.952
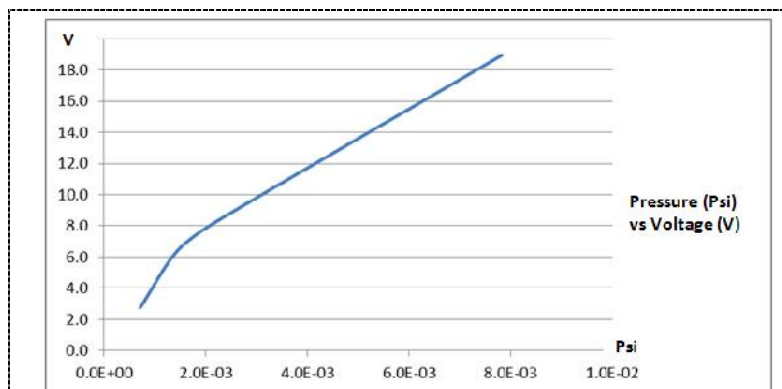
Figure 6. Comparison of Voltage (V) Generated and Equivalent Pressure Applied (Psi)

3.3 Characterization of Insole Pressure Sensor

To characterize the insole pressure system in real activities, the subject place the insole in a fitted shoe and the data is recorded. First the system is calibrated with no load pressure and measure the free condition. The pressure distribution curves were plotted in two difference activities; namely walk and run. Each subject first walked freely for 4 times. Following the calibrations, another 4 trials of "natural gait" were collected followed by ten other trials of various walking styles activities [8]. The same is done for running evaluation. The following figure shows the characterization of insole pressure sensor during walking and running.
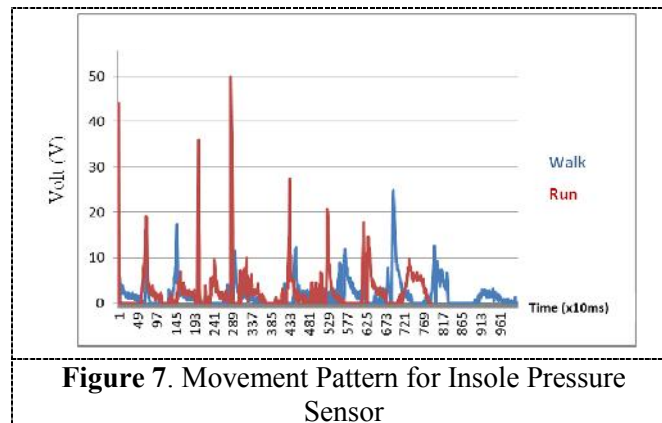
Figure 7. Movement Pattern for Insole Pressure Sensor

4. Conclusion

The development of the custom designed system which includes ultrasonic sensor, piezoceramic sensors, IMU, Arduino microcontroller and XBee modules is successfully performed and the performance of the system is analyzed in real life activities. The novelties of this research are wearable shoe attachment for wireless monitoring of foot clearance, orientation and sole pressure measurement during walking or while performing the daily routines in the house or outside of the house. The applications of this system are for monitoring the gait of the elderly, rehabilitation, injury prevention among athletes, biometric and early detection of diabetic ulceration. This system has high potential to be marketed especially for rehabilitation centers, sports centers, health centers, hospitals, research organizations and even stage performance training centre. We have presented a successful development and characterization of the system proved by the presented results. It is an evident to support the claim that this low cost low power consumption ultra-portable wireless i-SMART SHoE II system and its underlying concepts are realizable and practical.

5. References

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