33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

ZigBee-Based Wireless Multi-Sensor System for Physical Activity Assessment

Lingfei Mo, Shaopeng Liu, Robert X. Gao*, Dinesh John, John Staudenmayer, and Patty Freedson

Abstract— **Physical activity (PA) is important for assessing human exposure to the environment. This paper presents a ZigBee-based Wireless wearable multi-sensor Integrated Measurement System (WIMS) for in-situ PA measurement. Two accelerometers, a piezoelectric displacement sensor, and an ultraviolet (UV) sensor have been used for the physical activity assessment. Detailed analysis was performed for the hardware design and embedded program control, enabling efficient data sampling and transmission, compact design, and extended battery life to meet requirements for PA assessment under free-living conditions. Preliminary testing of the WIMS has demonstrated the functionality of the design, while performance comparison of the WIMS with a wired version on an electromagnetic shaker has demonstrated the signal validity.**

I. Introduction

DEFINED as any bodily movement generated by skeletal muscles, physical activity (PA) is important for maintaining good health. Regular PA increases the fitness level and exercise capacity, helps reduce risk factors such as obesity, diabetes, blood pressure, blood lipid abnormalities, improves cardiovascular system, and extends life expectancy [1]. Furthermore, it has been noted [1] that the recent increase in chronic diseases such as obesity and diabetes is directly correlated with the level of PA that people are engaged in on a regular basis, as well as exposure to environmental pollutions, e.g., pollutant or radioactive particles in the air, which may have high impact and therefore develop diseases in genetically predisposed people [2]. Accurate monitoring and assessment of PA, as well as the exposure conditions in the environments where PA is being done, provide valuable insight into the realistic behavior of the person engaged in such activities, thus is of high interest to the research community.

Properly constructed PA assessment methods should be able to recognize PA type, duration, and intensity, and quantify the energy expenditure during the physical activities. Direct and indirect calorimetry has been employed to quantify the intensity of activities monitored. For example, energy expenditure in terms of the heat loss of subjects was assessed accurately by measuring the heat exchange of a heat-sink direct calorimeter [3], a chamber maintained at a constant temperature by an air-conditioning unit. An indirect calorimeter such as a respiratory exchange system [4] calculates energy expenditure by measuring the oxygen consumption and carbon dioxide release through the use of a mouthpiece. These techniques, though accurate in assessing PA intensity, are laborious to use, and invasive to the subjects, limiting application in free-living environments.

In contrast, PA assessment using accelerometers offers non-invasive measurement, low subject burden, and low cost [5]. Studies [6] have reported good results in identifying PA intensities. However, using accelerometer alone is insufficient for distinguishing different types of activities [6]. Furthermore, such technique does not provide access to the quantification of environmental exposures.

Recent advances in sensing technology, low-power circuit design, and wireless communication have enabled the design of wireless sensor networks (WBANs or WBSNs) for monitoring personal health continuously and unobtrusively in free-living environments [7]. These WBANs generally consist of multiple sensors integrated with microprocessors that are able to transmit and receive data wirelessly. ZigBee is a standardized wireless protocol built on top of the IEEE 802.15.4 standard, characterized by low power consumption, low data rate, and low cost, and has demonstrated success for physiological measurement [8]. Compared with Bluetooth and WIFI, ZigBee allows a system to resume operation from "sleep" almost instantly, thus enabling the capability of realizing energy efficient wireless communication. Given that the ZigBee protocol is designed for wireless networks with a large number of sensors and longer data transmission range than typically seen in WBANs, it is necessary to modify the hardware and software designs of the WBANs for optimized energy consumption and improved reliability in real-time PA monitoring on a ZigBee platform.

Motivated by the increasing demand for advanced PA assessment technique in free-living environments with minimal subject burden, a ZigBee-based wireless multi-sensor integrated measurement system (WIMS) has been designed, prototyped, and experimentally evaluated under laboratory controlled condition. Energy efficiency and communication reliability for the wireless system have been focused. Besides using the accelerometers to measure bodily motion, a piezoelectric displacement sensor and an ultraviolet (UV) sensor have been integrated into the WIMS design to measure breathing and the environmental context, respectively. Comparison with a previously developed wired version of the device has shown good agreement in terms of

Manuscript received April 15, 2011. This work was supported by National Institutes of Health under Grant UO1 CA130783.

Lingfei Mo, Shaopeng Liu and Robert X. Gao* are with the Electromechanical Systems Laboratory, Department of Mechanical Engineering, University of Connecticut, Storrs, CT 06269, USA. (phone: 860-486-7110; fax: 860-486-5088; e-mail: rgao@engr.uconn.edu).

Dinesh John and Patty S. Freedson are with the Physical Activity and Health Laboratory, Department of Kinesiology, University of Massachusetts Amherst, MA 01003, USA.

John Staudenmayer is with the Department of Mathematics and Statistics, University of Massachusetts Amherst, MA 01003, USA.

the signal validity, confirming the effectiveness of the WIMS.

II. System Design

A. Configuration

The WIMS is designed to acquire real-time data of human subjects when engaged in PAs, and extract PA-related characteristics for improved assessment of physical activity. For clinical acceptance and practical applications, the WIMS should be easy to use, pose minimal burden to subjects, with an extended battery life. Fig. 1 illustrates the overall configuration of the WIMS, which collects data from the sensors worn by human subjects. Signal features are then extracted from the sensor data and fused for recognition of PA and prediction of associated energy expenditure. The WIMS consists of four sensors:

- Two triaxial accelerometers, placed at the dominant hip and dominant wrist, assess the body and arm motions, which are characteristics of the PA degrees;
- One piezoelectric displacement sensor, wrapped around the abdomen (which is convenient to wear) , measures the expansion and contraction associated with ventilation (breathing rate and volume);
- One ultraviolet (UV) photodiode detects the environmental context (indoor or outdoor) where activities are performed and is integrated with the wrist accelerometer into the same sensor package for maximum exposure to the ambient environment/light.

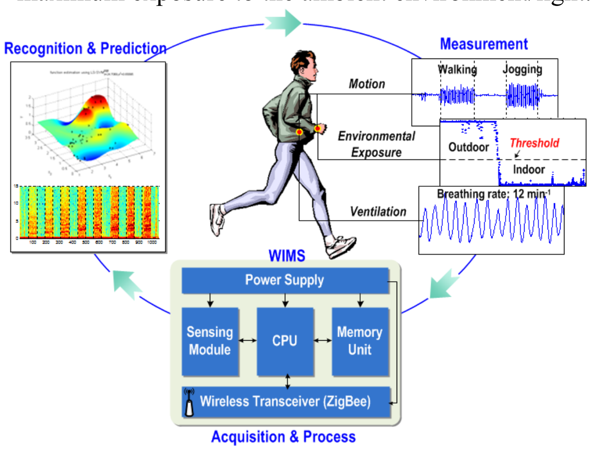

Fig. 1. Overall system architecture of the WIMS.

B. WIMS Realization

The WIMS consists of three units: the Abdominal Unit, Wrist Unit, and Hip Unit. Figure 2 shows the architecture and wireless communication scheme of the WIMS.

Each unit includes an 8-bit microcontroller (MCU) and a ZigBee module. The Abdominal Unit includes a piezoelectric displacement sensor for assessing respiration related characteristics, such as breathing rate and volume. The Wrist Unit contains a triaxial accelerometer to measure the arm/upper body motions, and an UV photodiode to detect the environmental context (indoor vs. outdoor). The Hip Unit includes another triaxial accelerometer for assessing the body/chunk motions. The signals recorded by the Abdominal and Wrist Units are wirelessly transmitted to the Hip Unit, where all the data can either be stored in a 2-GB micro secure digital (SD) card or wirelessly transmitted to a computer via a ZigBee module.

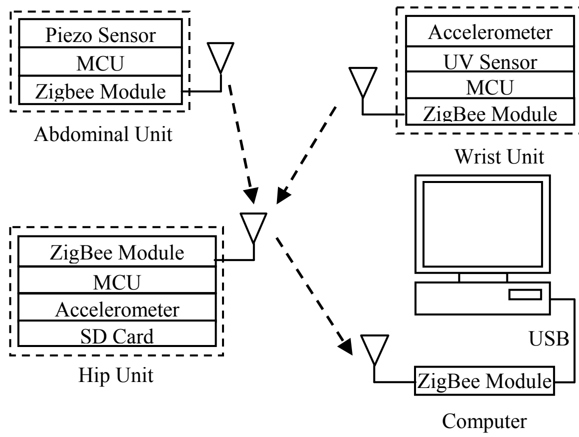

Fig. 2. Architecture of WIMS

C. Hardware Design

An illustration of the hardware design of the WIMS is shown in Fig.3. Each unit consists of the same type of MCU and ZigBee Module onboard. The MCUs (MC9S08QE128, Freescale) integrate a 12-bit analog-to-digital converter (ADC) on-chip for digitizing the sensor signals. The ZigBee modules (XBee-PRO, Digi International Inc.) were designed to operate according to the ZigBee protocol in the ISM 2.4 GHz frequency range, and support the needs for low-cost, low-power wireless sensor networks. To realize compact design, the ZigBee modules were located on the back of each circuit board. The modules work together with an XBee Explorer Dongle (WRL-09819, SparkFun Electronics Inc.), which is connected to the computer for data received by the computer, as well as for modem parameter configurations and firmware updates of the ZigBee modules. The destination addresses of the ZigBee modules in the Abdominal Unit and Wrist Unit were set as the address of the module in the Hip Unit, while the destination address of the ZigBee module in the Hip Unit was set as the address of the XBee Explore Dongle. Such an arrangement enables the Abdominal Unit and the Wrist Unit to only transmit data to the Hip Unit and the Hip Unit to only transmits data to the computer, avoiding data conflictions. Also, each unit accommodates a 3.7-V Li-polymer battery and associated charging circuitry via a micro USB connecter, enabling flexible charging for long-term monitoring.

D. Control and Communication Protocol

The program flow control and communication protocol maximizes battery life with respect to the sampling frequency and transmission rate. The Abdominal Unit transmits data on breathing, and the Wrist Unit transmits data on bodily motion and environmental context. These sensor data are sampled and transmitted to the Hip Unit every 33.3 ms (30 Hz). The program flow charts of the Abdominal and Wrist Units are shown in Fig. 4 (a) and (b). The CPU and the ZigBee module are switched into the sleep mode for energy conservation after the sensor data transmission is completed. In comparison, the Hip Unit keeps listening to the channel for incoming data from the other two units. If a data package from the Abdominal or Wrist Unit is received, the Hip Unit will analyze the data and update the corresponding data buffer of the Abdominal or the Wrist Unit. Once the transmission is completed, the Hip Unit stores all data into the SD card or send them to a computer, as shown in Fig. 4(c).

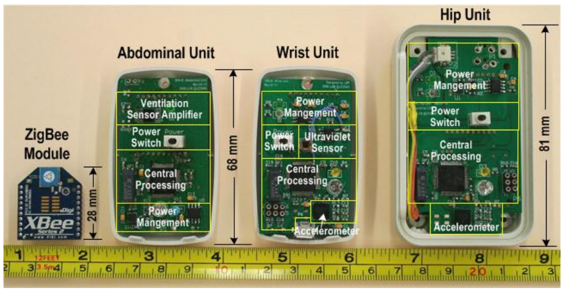

Fig. 3. Illustration of the WIMS prototype

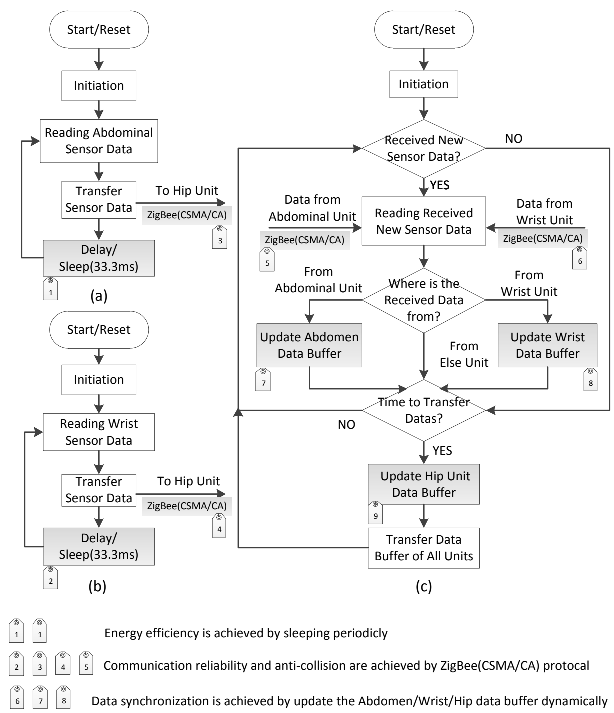

Fig. 4. Program flow charts of the WIMS. a) Abdominal Unit, b) Wrist Unit. c) Hip Unit

III. Experimental Performance Evaluation

A. System Testing and Real-time Display

To test the functionality of the WIMS, data sampled from the four sensor signals was transmitted to a laptop computer and displayed through a real time display program built on the MATLAB platform. The WIMS is worn by a human subject (Fig. 5), who performed various activities. A representative sample of signals from the accelerometers at the hip and wrist (taken when the subject was walking), the ventilation sensor (one normal breath and four deep breaths), and the UV sensor (outdoor and indoor) are shown in Fig. 6. In such real-time displaying mode, the Hip and the Wrist Unit can last for 16 hours with a 370 mAh Li-polymer battery. The Abdominal Unit was able to last for about 8 hours, using the same battery.

Fig. 5. Illustration of the WIMS on a human body.

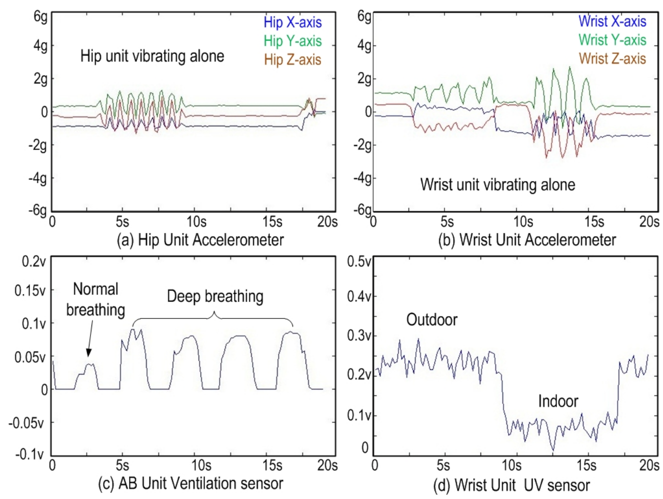

Fig. 6. Signals of the four sensors in the WIMS: (a) Accelerometer in the Hip Unit, (b) Accelerometer in the Wrist Unit (c) Piezoelectric sensor in the Abdominal Unit, (d) UV sensor in the Wrist Unit.

B. Shaker Testing of Signal Validity

To evaluate validity of the wireless design with respect to a wired version (called IMS), which serves as a reference base and previously evaluated experimentally by 300 test subjects [9], a comparison test on a permanent magnet shaker (ET-139, Labworks) has been performed. The shaker was set to vibration with an amplitude of 0.24 inch, in the frequency range of 2-6 Hz. Fig. 7 shows the experimental setup and an example of the testing signals of the accelerometer *x*-axis from the hip units of both the wireless and wired devices. The accelerometer data of the WIMS were transmitted to a nearby computer through ZigBee, and the data of the IMS were stored into an embedded secure digital card.

Accelerations from each of the three axes of the WIMS and IMS were compared and quantified, using the root mean squared error (RMSE) and correlation coefficient as criteria measures. The comparison results as shown in Table I have demonstrated that under a same condition, the WIMS reports the same accelerometer outputs as the wired sensors, with very small errors and high correlations. This indicates that the WIMS has the same performance for predicting the PA activity type and energy expenditure as the IMS [9].

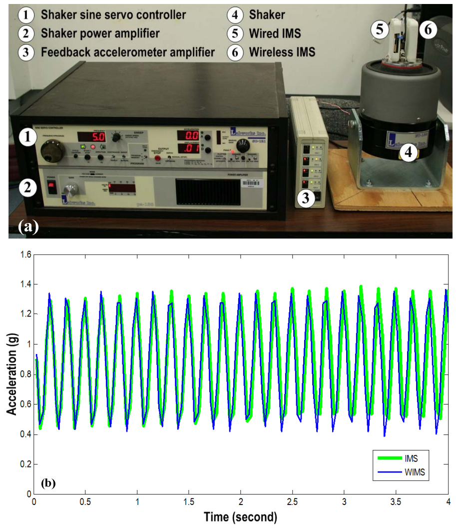

Fig. 7. Performance comparison between WIMS and IMS. (a) Experiment setup; (b) An example of testing signal (*x*-axis of hip accelerometer).

TABLE I
SIGNAL COMPARISON BETWEEN THE WIMS AND WIRED IMS

Accelerometer[a] Axis		Shaker Frequency (Hz)				
		2	*3*	*4*	*5*	*6*
X	*RMSE*	0.007	0.007	0.019	0.034	0.060
	Correlation	0.97	0.99	0.97	0.95	0.92
Y	*RMSE*	0.008	0.012	0.022	0.034	0.057
	Correlation	0.95	0.94	0.95	0.95	0.93
Z	*RMSE*	0.005	0.007	0.019	0.033	0.059
	Correlation	0.97	0.99	0.96	0.95	0.92

[a]Results based on accelerometers placed at hip.

C. Data Analysis and Performance Comparison

Experiments have been performed for predicting the metabolic equivalent of task (MET) of human subjects engaging in activities of various intensities. The MET is the ratio of activity energy expenditure to resting energy expenditure and expresses the absolute intensity of a given activity in multiples of resting metabolic rate. MET can be measured by the body's oxygen intake.

A total of 19 male and 31 female subjects were recruited for testing. METs were measured with a portable indirect calorimetry respiratory gas exchange system (Oxycon Mobile, Cardinal Health), which serves as a criterion measure. The respiratory gas exchange system, secured to the subject by an adjustable vest, provides physiological measurements such as breathing rate, ventilation volume, and the MET of each activity. For the WIMS, a multi-sensor data fusion algorithm [10] based on the Support Vector Machines (SVM) has been developed to predict METs by fusing signals from the accelerometers in the hip and wrist units and ventilation sensor. Fusion with UV data is work in progress.

Figure 8 shows a comparison between the measured and predicted MET values. A total of fourteen different types of activities have been measured and predicted. The predicted and measured values have shown to be in good agreement with a R^2 value of 0.95, a root mean squared error of 0.67 METs, and a mean absolute error of 11.0%. These results confirm the performance of the new WIMS device in monitoring physical activities.

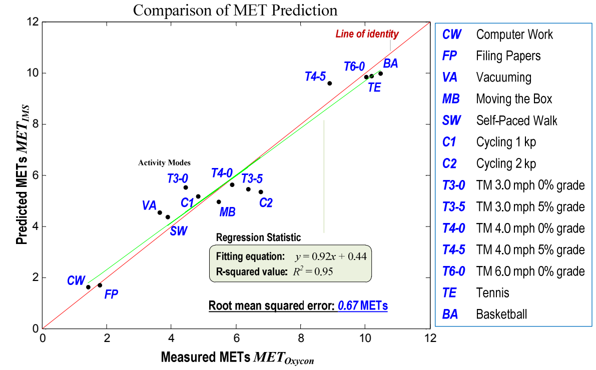

Fig. 8. Comparison of measured and predicted METs of different activities.

IV. CONCLUSIONS

A ZigBee-based Wireless wearable multi-sensor Integrated Measurement System (WIMS) for assessing physical activity is presented. Through low power design and embedded control, battery life is optimized, enabling WIMS's use under free-living conditions. Shaker experiments have shown good agreement between WIMS and a wired reference device. Real life related comparison with different physical activities have been planned to improve system reliability for *in-situ* large-scale subject testing and PA assessment.

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