Monitoring Human Movements at Home Using Wearable Wireless Sensors

Chao Chen, Carlos Pomalaza-Ráez

Indiana University - Purdue University, Fort Wayne, Indiana, USA

Abstract

Recent developments in wireless and sensor technologies can help create a smart home health care environment at low cost, allowing patients to have their physiological signs monitored while staying at home. This paper describes an ongoing project on the design and building of a wearable wireless sensor system to acquire data concerning physical activities of a person in need of medical care. A waist-mounted triaxial accelerometer unit is used to record human movements. Sampled data are transmitted using an IEEE 802.15.4 wireless transceiver to a data logger unit and passed to a PC for analysis. The architecture design, the prototype implementation, and initial validation tests of the monitoring system are presented.

Keywords:

Physiologic monitoring, accelerometer, IEEE 802.15.4

Introduction

Today's health care systems are burdened by the increasing number of elderly and disabled people needing medical support. If the physical activities of these people can be monitored reliably at home and at a low cost, it will have a tremendous effect on reducing the gap between the need and the capability of the current health care systems. Recent developments in communication and sensor technologies have paved the road for creating a smart health care environment. Patients can stay at home and at the same time have their vital physiological signs monitored. When an abnormal condition occurs, the patients can easily access their caregivers, receiving assessment and treatment in a timely manner.

Assessing abnormal movements resulting from poor health is essential for monitoring patients' health status and quality of life. In this paper, we describe a design project that uses wearable sensors to measure and collect signals with information about the motions of a person in need of medical care. Such signals are wirelessly transmitted and recorded for a thoroughly post analysis. To measure human movements, a triaxial body-fixed accelerometer is selected for its low price, small size, capability of continuous measurement, and ease of integration. IEEE 802.15.4 is selected as the wireless transmission standard because of its short-range, low-cost, and low-power characteristics. The implemented system allows for inexpensive and unobtrusive monitoring during normal daily activities at home or in a nursing home environment.

The remainder of this paper is structured as follows. Section II describes in general our system architecture and the selection of the key components. Section III explains in more detail the design and implementation of this system. Section IV presents initial experimental results. Section V concludes this paper with discussions and an outline for future work.

System Description

The main goal of this project is to build a working prototype of a wearable wireless sensor system that allows for the acquisition of data concerning physical activities of a person in need of medical care at home. The data should carry enough information for the post analysis and possible characterization of movements. The wearable sensor system should be able to operate for long periods of time (possible days) without the need to have its batteries replaced.

Overview

Our system architecture consists of two main components: the *wearable sensor unit* and the *data logger unit*, as shown in Fig. 1. The wearable sensor unit is carried by a person, and it measures the person's movements. The measured data are sampled via an analog-to-digital converter (ADC) and fed into a microcontroller. The sampled data are then transmitted wirelessly to a data logger unit, which is fixed at a location close to a grid power source. The measured data will be downloaded to a PC through a cable connection and analyzed using software programs.

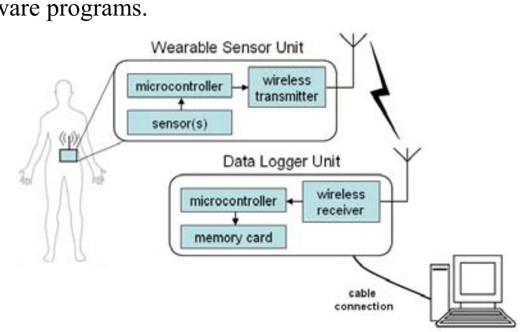

Figure 1- Overview of the wireless human movement monitoring system.

Selection of Wearable Sensor

Inertial measurement components sense either translational acceleration or angular rate. The advances in micro-electromechanical systems (MEMS) and other micro-fabrication techniques have greatly reduced the cost and size of these devices, and they can be easily embedded into wireless and mobile platforms. Gyroscope and accelerometer are two common inertial sensors that can be used to capture human movements continuously.

Accelerometers measure both static (*e.g.*, gravity) and dynamic (*e.g.*, vibration) acceleration, both including the always-present gravitational acceleration *g*. If the angle of the sensor with respect to the vertical is known, the gravity component can be removed, and velocity and position can be determined by numerical integration. Movement in three dimensions can be determined using accelerometer measurements over three orthogonal axes.

Gyroscopes are used to measure angular velocity. If the initial angle is known, integration over time provides the change in angle. Compared with accelerometers, gyroscopes have drawbacks such as higher power consumption, higher cost, possibility of drift, and sensitivity to shock.

We have chosen the accelerometer to measure human movements in our project because of its low price, small size, capability of continuous measurement, and ease of integration. Experimental research has shown that normal daily activity can be recorded by attaching accelerometers to the human body with minimum discomfort of the subject [1][2][3][4]. Accelerometers placed at the waist or thigh have been used to resolve resting states, such as sitting, standing and lying, and activities including walking, falling, and transition between resting states [5][6]. In our project, continuous recordings are wirelessly transmitted and stored on a memory card in the data logger unit and then downloaded to a PC for analysis.

Selection of Wireless Standard

The designed product is expected to be used indoor such as at home or in a nursing home environment, therefore a short-distance wireless communication system is more appropriate for this application. Two types of wireless communication standards are suitable for this application: IEEE 802.15.1 and IEEE 802.15.4; both operate in the 2.4GHz unlicensed frequency band.

IEEE 802.15.1 is adapted from Bluetooth, which is a telecommunications industry specification for short-range RF-based connectivity for portable devices. Bluetooth is designed for small and low cost devices with low power consumption. Since Bluetooth is geared towards handling voice, images, and file transfer, it has a data transfer rate on the order of 1Mbps with a complex protocol. The operational range for Bluetooth is around 10 meters. With amplifier antennas its range can be boosted to 100 meters, but with higher power consumption.

IEEE 802.15.4 specifies the physical layer and medium access control for wireless personal area networks (WPANs) which focuses on low-cost, low-speed ubiquitous communication between devices. It is designed for applications with a transmission range of up to 100 meters and data transfer rates of 20-250 kbps. 802.15.4 supports a basic master-slave configuration suited to static star networks of many infrequently used devices that talk via small data packets. Compared with Bluetooth, 802.15.4 is more power-efficient because of its small packet size, reduced transceiver duty cycle, reduced complexity, and strict power management mechanisms such as power-down and sleep mode.

It is clear that IEEE 802.15.4 is the better choice for our proposed design that requires short range wireless communication between low-cost, low-power, battery-operated devices for monitoring purposes.

System Implementation

This section explains the details of our design, including the selection of devices, work flow description, as well as power, size, weight, and cost analysis.

Wearable Sensor Unit

The wearable sensor unit is attached to the waist. We select Freescale MMA7260Q triaxial analog accelerometer as the measurement device, shown in Fig. 2 (left). This accelerometer has four different measurement ranges (±1.5*g*, ±2.0*g*, ±4.0*g*, and ±6.0*g*) that can be dynamically set by two input pins. Each range provides different measurement sensitivity. The accelerometer continuously records human movements in terms of accelerations in all three axes. The lower ranges (*e.g.,* ±1.5*g*) are used primarily for accurate measurements of small motions, whereas the higher ranges (*e.g.,* ±6.0*g*) are used primarily for measurements of vibration and impact generated during activities such as running and falling. The MMA7260Q accelerometer has low power consumption with 2.2V~3.6V and 500μA at the normal condition. It can also be set to a low-current inactive mode (*i.e.*, sleep mode) of only 3μA operation current through a SLEEP pin, which further conserves power.

The measured data are fed into a microcontroller and sampled via an ADC. We select the Silicon Labs C8051F353 microcontroller with a built-in 24/16 bit ADC in our design. The microcontroller does simple processing on the data and set the working mode of the accelerometer accordingly. Processed data are fed into an IEEE 802.15.4 wireless transceiver and sent to the data logger unit. For our design, the XBee® 802.15.4 radio modem from MaxStream is chosen as the wireless transceiver, as shown in Fig. 2 (right). It can operate under transparent mode with a simple connection with a microcontroller. With a chip antenna, it operates up to 30 meters indoor. The transmission range can be further increased to 90 meters by using a whip antenna. The XBee module has a low maximum transmit power of 1mW and a high receiver sensitivity of -92dBm.

Figure 2- Left: MMA7260Q accelerometer breakout board. Right: XBee® 802.15.4 radio modem with a chip antenna.

Fig. 3 depicts the workflow of the accelerometer. Initially the accelerometer is put in sleep mode and wakes up periodically at a low frequency (*e.g.*, every 10 sec), taking a sample with a low measurement range (*e.g.*, ±1.5*g*) and high measurement sensitivity. This allows minimum power consumption when a person is in REST mode. Once a measurement reading exceeds a certain value *thresh*1, which means that this person is now in ACTIVE mode, continuous measurement will be taken with the sleep mode disabled. The sampling rate is set by the microcontroller in the range of 10-100Hz, as it has been found that the frequency of human induced activity ranges from 1 to 18Hz [1]. If the reading exceeds another value *thresh*2 (>*thresh*1), a higher measurement range (*e.g.*, ±6.0*g*) and lower measurement sensitivity will be set. This procedure helps distinguish between SLOW motion and ABRUPT motion when the person is in ACTIVE mode.

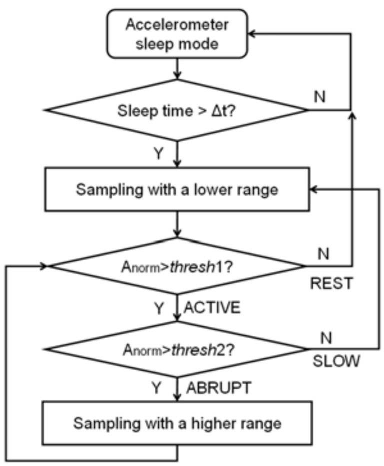

Figure 3- Workflow of the accelerometer.

The level of activity can be calculated using the normalized magnitude value of the acceleration (A_{norm}) that involves measurements from all three axes as follows:

$$A_{norm} = \frac{1}{T}\left(\int_0^T |x(t)|dt + \int_0^T |y(t)|dt + \int_0^T |z(t) - g|dt \right), \qquad (1)$$

where $x(t)$, $y(t)$, and $z(t)$ refer to the frontal, side, and vertical samples, respectively; T is an observation interval. Because of the Earth's gravity, a positive 1*g* output is always present in the vertical measurement $z(t)$.

Data Logger Unit

The front-end of the data logger unit is a wireless XBee transceiver. Upon receiving the measurement data from the wireless interface, the XBee transceiver forwards the data directly to the microcontroller for processing. We choose C8051F344 from Silicon Labs as the microcontroller in the data logger unit. It has convenient USB interface with a flash memory stick or directly to a PC. The processed data then serve as the basis for the calculations and software development involved in the characterization of movements. Other measurement metrics besides A_{norm} and statistical analysis algorithms will also be explored to characterize and classify movements in greater detail. The analysis of the sampled data allows possible characterization of human movements such as sitting, standing, rotation, walking, and jumping. Moreover, abnormal activities such as falling can be detected through the analysis.

Power, Size, Weight, and Cost Analysis

Table 1 lists the power, size, and weight analysis for the major components in the wearable sensor unit. We select a 3.7V Li-Ion rechargeable battery pack with 6600mAh of energy as the power source. Most power is consumed by the wireless transceiver. In the worst case, if the XBee RF modem is continuously transmitting, the wearable unit can be used for more than 120 hours without recharging. If the transceiver is active for 10% of the time and in standby mode for 90% of the time, the wearable sensor unit can be operated for more than 600 hours (~25 days) without changing battery. Therefore, adding some pre-processing in the microcontroller and dynamically changing the sampling rate based the human activity level can reduce the frequency and amount of data transmitted over the air, which in turn saves energy.

The size of the whole sensor unit prototype (including the casing) is limited to 75×60×30mm, and the weight is less than 10oz. The whole unit can be wearable without much disturbance to the person. Since the data logger unit is connected to a fixed power source, the power consumption, size, and weight will not be an issue.

Table 1- Power, size, and weight analysis for the wearable sensor unit

Component	Typical current (mA)	Size (mm)	Weight (oz)
MMA7260Q accelerometer	0.5	6×6×1.45	0.05
C8051F353 microcontroller	5.8	9×9×1.6	0.05
XBee 802.15.4 transmitter	45	25×28×2.8	0.14
Li-Ion 18650 battery pack	-	69×54×18	9.0

The cost to build the overall system prototype is around 150 US dollars, which makes it applicable for home use. Moreover, a single data logger unit can be used along with several wearable sensor units because of the built-in capability of the XBee RF module to form a star network. This allows multiple users to share the same data logger unit, which is especially convenient in a nursing home scenario.

Measurement Tests

In this section, we present two measurement studies that validate the feasibility of our design: Accelerometer measurement test of typical human movements and interference test of the 802.15.4 wireless transceiver in a home scenario.

Accelerometer Measurement Test

We first test the accelerometer measurement by attaching the wearable sensor unit to a person's waist. The sampled data of acceleration reading is read directly from the C8051F353 microcontroller with the wireless transceiver bypassed. The sampling frequency is 40Hz for each axis.

Fig. 4 presents typical accelerations obtained during a 10-s measurement of slow-mode activities such as sitting, standing, and transitions between sitting and standing. It can be seen that different activities show different patterns in the acceleration measurement. Since the movement is mainly in the vertical axis, the acceleration over z-axis depicts the pattern more clearly. We also calculate the normalized magnitude value (A_{norm}) using Equation (1) and setting T=0.5sec. The change of A_{norm} over time is plotted in Fig. 5, showing that A_{norm} does reflect the level of activity. For example, A_{norm} is higher during periods of sit-stand and stand-sit transitions, but lower while sitting or standing. Therefore, it is possible to classify different human movements based on the acceleration recording. As future work, more advanced numerical and statistical analysis tools will be developed to further characterize different activities and detect abnormal activities such as falling.

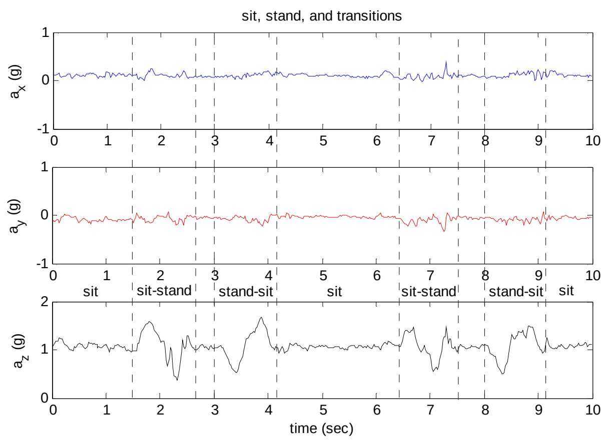

Figure 4- Acceleration measurement over three axes.

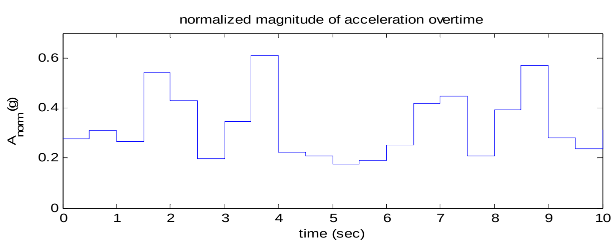

Figure 5- The normalized magnitude of acceleration (A_{norm}) during the sit-stand-transition test.

Wireless Interference Test

Medical monitoring applications require high reliability in data collection. However, IEEE 802.15.4 operates in the 2.4GHz license-free industrial, scientific, and medical (ISM) band, which is shared by several other wireless standards, such as the IEEE 802.11 wireless local area network (WLAN). With the growing popularity of home devices with WLAN interfaces, wireless monitoring system at home using 802.15.4 standard will inevitably face interference from these devices. Moreover, most household microwave ovens operate on a frequency of 2.45GHz. The interference from microwave ovens at home cannot be ignored either. There have been some experimental tests to evaluate the impact of 802.11 on the performance of 802.15.4 performance [7][8][9]. Their work focuses on the worst case by deliberately putting 802.11 and 802.15.4 devices right next to each other. On the other hand, we perform the measurement tests in an apartment scenario, where the interference comes from WLANs of surrounding neighbors. We believe that our test environment is closer to the proposed smart home medical application scenario.

We have performed a series of experimental tests to evaluate the impact of WLANs and microwave ovens on the performance of 802.15.4 transmission. Specifically, we use an XBee 802.15.4 starter development kit that comes with two XBee RF modules. One module (*i.e.*, the "base" module) is mounted to a USB board that connects to a PC. The other module (*i.e.*, the "remote" module) functions as a repeater by looping data back for retransmission. We used this kit for a point-to-point test, where data are transmitted from the base module, the remote module receives and retransmits data back, and the base module picks the data and compares with the data sent.

All tests are performed in a one-bedroom apartment scenario on a weekend afternoon. The longest distance between two points in the apartment is about 10 meters, which is within the transmission range of the XBee module. So the two modules should be able to receive each other's data successfully if no interference is present. In each test run, the base module send out 1000 identical data messages, each with 32 characters' length. The timeout value for data reception is set as 100 msec. The result for each test case is an average of 10 runs.

Co-existence with 802.11

The overlapping frequency allocations of 802.11 and 802.15.4 are shown in Fig. 6. Most WLAN wireless routers operate on one of the non-overlapping channels (*i.e.*, channels 1, 6, or 11) with a 25MHz bandwidth. 802.15.4 devices in the 2.4GHz band have 16 non-overlapping channels to choose from, each with a 5MHz bandwidth. The output power of 802.15.4 is typically as low as 0dBm, whereas the 802.11 devices usually operate with a much higher power at 15dBm or above.

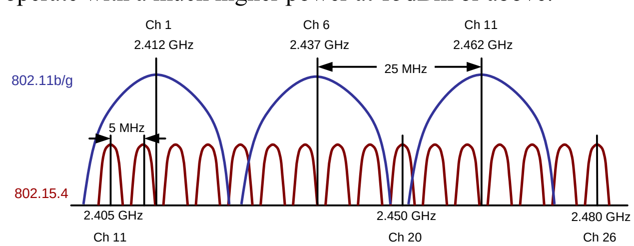

Figure 6- 802.11and 802.15.4 channels in the 2.4GHz band.

In our test scenario, neighbors live close in the apartment building. During our measurement tests, eight 802.11g networks are consistently present. Among them, three are with good to very good signal strength (Two are operating on channel 1 and one is on channel 11). The ones with fair but recognizable signals are scattered in channels 1, 6, and 11. Besides these eight networks, a total of nine other different WLAN networks have also appeared during the tests.

We first set our XBee module to work on channel 12 with a center frequency of 2.41GHz. This is a worst case that the offset to the strongest 802.11 channel (*i.e.*, channel 1 in our case) 1 is only 2MHz. We test the data success ratio under different power levels and the results are listed in Table 2. When the XBee modules are transmitting at a lower power of -10dBm, the average data success ratio is slightly lower and the standard deviation is higher. Next, we let XBee modules operate on channel 20 with a center frequency of 2.45GHz, which is in the middle of 802.11 channel 6 and channel 11. In this case, there is only minor interference from surrounding 802.11 devices: The data success ratio is always 100% even when the XBee modules are transmitting at the lowest power level of -10dBm. The results show that 802.15.4 devices do experience interference from 802.11 signals. However, such interference can be reduced by selecting a channel that is further away from the three busiest 802.11 channels.

Table 2- Co-existence test results for 802.11 and 802.15.4

Power level of Xbee modules	802.15.4 Channel	Data success ratio	
		mean	std.
0dBm (1mW)	12	99.36%	0.39%
-10dBm (100μW)	12	99.21%	0.75%
-10dBm (100μW)	20	100%	0%

Co-existence with Microwave Oven

Since microwave ovens operate on the frequency of 2.45GHz, we set the XBee modules to work on channel 20 with a center frequency of 2.45GHz. To test the worst case, we put the XBee remote module right next to the microwave and set the transmit power to -10dBm. Table 3 shows that when the microwave oven is OFF, there is no data loss (Note that channel 20 also experiences less interference from WLAN). When the microwave oven is ON, the data success ratio is reduced to 96.85% with a high standard deviation of 3.22%. However, if we put the remote module to about 2 meters away, the influence from the microwave oven can be removed.

Table 3- Co-existence test results for microwave oven and 802.15.4 (power level = -10dBm, channel=20)

Microwave status	Data success ratio	
	mean	std.
OFF	100%	0%
ON	96.85%	3.22%

Discussions and Future Work

This paper describes an ongoing project that builds a wearable wireless sensor system to acquire data concerning the physical activities of a person in need of medical care. The detailed design involving a triaxial accelerometer and an IEEE 802.15.4 wireless transceiver is explained. The workflow and analysis of the design shows that the human movements monitor system is inexpensive, energy efficient, and unobtrusive to the human object. Initial measurement tests verify that acceleration measurements can be used to classify human movements. Although 802.15.4 devices experience interference from nearby 802.11 networks, such impact can be reduced by selecting an appropriate operating channel. Furthermore, channel 20 should be avoided when 802.15.4 devices are in close proximity to a microwave oven.

In the near future, we will test the whole system extensively and investigate more power saving mechanisms (e.g., preprocessing data in the microcontroller to reduce the amount of data to be transmitted over the air). Advanced numerical and statistical analysis tools will be developed to characterize and classify different activities and detect abnormal activities such as falling. Moreover, the coexistence issue of 802.11 and 802.15.4 will be evaluated in greater detail.

Acknowledgments

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