Wireless Logger for Biosignals

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Abstract: This work proposed a novel 4-channel wireless data logger that uses electromyography (EMG), electrocardiograph (EKG), and accelerometer transducers for field measurements of biosignals. The logger, which weighs 102 g (including the battery), continually acquires 4-channel 16-bit analog signals at 1000 Hz/channel. The acquired data are saved on a microSD memory card for subsequent analysis. The logger utilizes a ZigBee transceiver module that transmits acquired data to a remote receiver. The logger can run for over 6 consecutive hours at full load when powered by two 860 mAh batteries. The remote receiver unit, connected to a PC or laptop via a USB interface, was controlled by Window-based monitoring software for communicating with the logger. The monitoring software programmed by Borland C++ Builder operated the logger and monitored real-time data sent from the logger feasibility. The experimental results demonstrate that the system is reliable and feasible for field measurements of biosignals for a prolonged period.

Keywords: EKG; EMG; telemetry; data acquisition; monitoring system

1. Introduction

Data loggers or telemetry devices have been widely applied in clinical assessment and home-care technology, and on worksites to assess the physical workload of workers performing various industrial tasks [1–4]. Such devices are generally portable or wearable, lightweight, battery powered, and capable of storing or telemetering data [5–11]. Biosignal data collected by loggers or telemetric devices typically include that of joint angles, heart rate, electromyography (EMG) data of muscles, and inclination of the neck. trunk, and upper arms. Conventional data loggers have limited capacity to store large amounts of data and, thus, are generally limited by a low sampling rate, short sampling period or an ability to only store processed data periodically. A multi-channel portable logger with a large storage capacity and high sampling rate was developed by Liu *et al.* (2006) for worksite measurements of biosignals [12]. However, that logger does not telemeter data to a remote monitoring system such that investigators can monitor on-going processes during data acquisition.

A logger with telemetric capability eliminates unintentional loss of experimental trial data during onsite data acquisition. During onsite measurement, an investigator may be far from the observed subject due to safety concerns, space limitations or subject migration. Investigators using portable data loggers without telemetric capability may encounter such adverse situations as malfunctioning

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sensors, broken wires, and power failure.

Several studies have developed wireless systems real-time monitoring for of home-care subjects and patients [6–9]. These systems acquire specific biosignals via an electrocardiogram (ECG) and electroencephalogram (EEG), and assess oxyhemoglobin saturation by pulse oximetry (SpO2), and heart rate, body temperature and blood pressure. These systems acquired biosignals at sampling rates <250 Hz. However, biosignals such as EMG signals generally require a sampling rate exceeding 1000 Hz [10]. Therefore, a wireless system with various sensor types and a high sampling rate is required for measuring physical workload of workers performing various tasks.

This study designs a portable logger system, capable of recording and monitoring biosignals, for field measurement of physical workloads of workers. The proposed logger system is integrated with a microcontroller and Zig-Bee wireless technology. This work describes the architecture and capabilities and assesses the feasibility of the proposed logger system.

2. Materials and Methods

2.1. System architectures and major components

Figure 1 shows the architecture of the proposed logger system, comprised of a portable logger unit and personal computer (PC)-based monitoring system with monitoring software. Two ZigBee modules are used for wireless data transmission. One module is integrated into the portable logger unit as a transceiver, while another module is utilized as the unit that receives data from the monitoring system. In addition to ZigBee module, the portable logger has signal-acquisition circuits for sensor signals, digital control circuits for data storage and telemetry, an analog-to-digital (A/D) converter for data acquisition, and a micro secured digital memory card (microSD

2.2. Portable logger unit

The portable logger unit is powered by DC +7.2V using two serially connected +3.6V rechargeable Li-ion batteries. The logger unit comprises the signal-acquisition circuit and digital control circuit, which are described as follows.

2.2.1. Signal-acquisition circuit.

The signal-acquisition circuit is powered by DC +5V, provided by a positive low dropout regulator (LT1117-5; Linear Technology Corp., USA) converted directly from the two batteries. The voltage regulator circuitry also provides +5V excitation voltage to the external transducers. The analog signals from the transducers, in the range of $\pm 10V$, are connected to differential amplifiers (INA159; Texas Instruments, Inc., USA). The signals are amplified and converted to 0-5V, and then A/D converted into digital data. The A/D converter (ADS8341; Texas Instruments, Inc., USA), powered by +5V, has a 4-channel multiplexer, 16-bit resolution, and maximum sampling rate of 100 kHz. The reference input for the A/D converter was set at +5V using a reference integrated voltage circuit (LT1460-5; Linear Technology Corp., USA) with a drift of 10 ppm/°C. A 500-Hz RC circuit was built in for each input signal to reduce aliasing of high-frequency noise.

2.2.2. Digital control circuit.

The digital control circuit is powered by +3.3V, which is provided by a LT1117-3 regulator, converted directly from the batteries. The control circuit has a digital input/output (I/O) circuit that controls data storage, the ZigBee module for wireless transmission, and an LED indicator for displaying system status. An 8-bit microcontroller (C8051F314; Silicon Laboratories, USA) powered by +3.3V controls logger operation. The clock frequency of the microcontroller is set to 22.1184 MHz using an external oscillator. Since the internal timer register of the microcontroller triggers sampling events, this external oscillator determines sampling rate accuracy. The timer register issues system interrupt at a rate of 1 kHz to initiate A/D conversion for the first channel, and minimize the time lag between channels. The succeeding channels were sampled consecutively at maximum speed.

The microcontroller simultaneously saves A/D converted data on the microSD card and telemeters data via the ZigBee module to the remote monitoring system. The microcontroller also receives control commands sent from the monitoring system by the receiver unit. The ZigBee module (XBee-Pro; Digi International, Inc., USA) conducts point-to-point connection, resembling a standard serial cable. and communicates with the microcontroller via universal asynchronous а receiver/transmitter (UART) interface at a maximum rate of 115,200 bps.

A 2-gigabyte microSD card is used for data storage. The microSD card was selected because of its current popularity as a transportable mass storage device. The card is 15mm×11mm×1mm and weighs only 0.5 grams. To accelerate the storage rate, acquired data are saved on the microSD memory card by sector (512 bytes). The second sector of the microSD storage is reserved for the trial allocation table (TAT). Moreover, the start sector and data length for each trial are saved using 4 bytes of the TAT sector sequentially. This allocation table permits storage of information for up to 64 trials. The data-storage format on the microSD card is the same as that used by Liu et al. (2006) [12].

An LED indicates the system status—Off, Working, and Standby. A circuit in the digital control module that detects low battery power maintains data-acquisition quality. The microcontroller stops data acquisition automatically when battery power is low.

2.3. Wireless receiver unit

The unit receiving telemetered data from the logger is powered directly via the USB interfaces of a PC or laptop computer, and comprises a ZigBee module and bridge circuit for the USB and serial UART. Personal and laptop computers currently utilize the USB interface as the standard interface for external devices. Therefore, the built-in UART serial interface of the ZigBee module requires a bridge (translating) circuit between the USB and UART serial interfaces. A commercial USB-UART serial bridge (FT232R; Future Technology Devices International, UK) is the selected bridge.

2.4. Monitoring software

Monitoring software, developed by Borland C++ Builder 6, runs on a PC or laptop computer using the Windows XP operating system. This program transmits commands to the logger to establish the data sampling and monitoring rates, and initiate or terminate a data-acquisition process. The monitoring rate is the data rate transmitted from the logger to the receiver unit, and is an integer fraction of the sampling rate. The monitoring software also reads logger data received by the ZigBee unit via a USB, and plots signal waveforms on the terminal screen. The software also stores data onto a local hard disk drive or a USB flash dongle.

2.5. Feasibility tests

Three laboratory tests and two field tests were conducted to assess the feasibility of the proposed logger system.

2.5.1. Data accuracy

Five sinusoidal signals with different frequencies and a root mean square (RMS) value of 1.77V were generated by a function generator. Each specific frequency waveform was acquired by the proposed logger at 1000Hz for 3 consecutive minutes. Accuracy of collected data was analyzed by comparing the frequency spectrum and RMS of the acquired waveform with those obtained from a digital oscilloscope (TDS 3024B; Tektronix, USA).

2.5.2. Data telemetry

Transmission distances of 3, 10, 20, 30, 50, and 100 m between the logger and monitoring system were tested. Two receiver antennas, a 5dB omnidirectional antenna and an 11dBi (decibel isotropic) directional antenna, and 2 logger antennas, a 3dB omnidirectional antenna and a 9dBi directional antenna, were tested. For each test condition, the logger started by telemetering 1000 data packets (16 samples/packet = 4 samples/ch \times 4 ch/packet) at a transmitting rate of 250 packets/s and a monitoring rate of 1000 samples/s/channel. When the transmission error rate exceeded 0.1%, the monitoring rate was reduced by 50% and the trial was repeated. For each test condition, the highest monitoring rate that achieved a success rate exceeding 99.9% was recorded.

2.5.3. Battery durability

Two serially connected 860mAh Li-ion batteries (BL-5B; Nokia) provided +7.2V and was tested for durability by running the logger continually. The logger continually acquired EMG signals from 4 active surface electrodes (SX230, Biometrics Ltd., UK) at 1000 samples/s during the test. The logger saved acquired data onto the 2-G-byte microSD card (SanDisk Corp., USA) and telemetered the data at a monitoring rate of 250 samples/s/channel. Lifetime of the battery operating the logger was recorded.

2.5.4. Dynamic field test

A 23-year-old subject wore the logger on his lower back via a belt while running on a 400-m course. The subject ran the first 100 m and then walked 300 m; this course was repeated 5 times. The subject's EKG and EMG signals from the left rectus femoris and gastrocnamius muscles were recorded simultaneously by the logger. The monitoring system was located at one end of the 400-m track. The data saved by the logger and monitoring system were checked to ensure no data were lost during the test period. The subject's heart rate was computed from the EKG R-R interval of adjacent QRS waveforms using Viewlog analysis software. The Viewlog software, programmed using LabVIEW 7.0 (National Instruments, USA) by Chen et al. (2006), was applied to download logged data from the microSD card and facilitated bulk data analysis and processing [13]. Experimental results for heart rate history and EMG signals were analyzed to confirm that they accurately reflect subject activity.

2.5.5. Prolonged field test

A 47-year-old investigator carried the logger in his pocket for acquiring EKG signals from 8:00 a.m. to 12:00 p.m.. The investigator first walked away from his office, down 2 floors, crossed a 200-m field, and climbed 4 floors of a building before giving a 50-min lecture. The subject then returned to his office and worked on a computer. Two hours later, he repeated the same course and returned to his office at 12:00 p.m. Recorded data was checked to ensure no data were lost during this test period. Subject heart rate was computed using the aforementioned method and examined to confirm that it reflected subject physical activities.



Figure 1. Architecture of the proposed logger system

3. Results

Figure 2 shows the proposed logger and its circuitry. All electronic components of the data logger, including the battery, weigh 102g and are enclosed in a 90mm×50mm×25mm case. The logger simultaneously records 4 analog signals from the EKG/EMG transducers or accelerometers. Each analog signal from a transducer is connected to the signal conditioning circuit via 1 of 4 Binder con-

nectors (Series 719; Binder GmbH & Co., USA) located on the logger bottom. These connectors also provide access to other pre-amplified analogue signals, ranging from -10V to +10V. One RP-SMA type connector located on the logger top is used as the antenna mount. Figure 3 shows the uncovered receiver unit of the monitoring system. All electronic components of the receiver unit 62g weigh and are enclosed in а 90mm×50mm×25mm case.

Feasibility test results show that the data acquired by the logger are accurate. All waveform frequencies and the RMS value obtained via spectrum analysis of logger data had absolute errors of <0.1% when compared with the corresponding oscilloscope readings (Table 1).



(a) (b) Figure 2. Logger (a) outward appearance with a 3dB omnidirectional antenna, and (b) inside



Figure 3. Data receiver unit with a 5dB omnidirectional antenna.

Table 1	. Frequency	and amplitude	accuracy of	data record	ded by the	logger c	ompared v	with c	scil-
	loscope rea	adings (oscillos	cope RMS =	1.77V)					

Oscilloscope frequency	Logger frequency	Logger RMS	Error (%)
10.17Hz	10.16~10.18	1.768~1.771	<0.1%
50.27Hz	50.25~50.29	1.768~1.771	<0.1%
98.19Hz	98.12~98.23	1.768~1.771	<0.1%
149.1Hz	149.06~149.17	1.768~1.771	<0.1%
198.3Hz	198.29~198.36	1.768~1.771	<0.1%

Telemetry test results demonstrate that the success rate of wireless data transmission is significantly and adversely affected by distance between the logger and the monitoring system and antenna type (Table 2). When using the 3dB and 5dB omnidirectional antennas, data was telemetered reliably over a 3-m distance at a monitoring rate of \leq 250 samples/s/channel. With the 9dBi and 11dBi directional antennas, the monitoring rate can be

increased to 1000 samples/s/channel at an indoor distance of 10 m, and to 500 samples/s/channel at an outdoor distance of 100 m. Test results indicate that the logger system telemetered data reliably at a rate of 250 samples/s/channel over a 50-m indoor range using the 3dB omnidirectional antenna for the logger and an 11dBi directional antenna for the receiver.

Table 2. Maximum monitoring rate (samples/s/channel) under various combinations of antenna
gains and telemetry distances with 99.9% of packets received successfully.

Telemetry	Ant	Test		
distance	5dB / 3dB	11dBi / 3dB	11dBi / 9dBi	environment
3m	250	500	1000	indoors
10m	125	500	1000	indoors
20m	125	250	500	indoors
30m	125	250	250	indoors
50m	n.a.	250	250	indoors
100m	n.a.	250	500	outdoors

The battery test result indicates that two serially connected 860mAh Li-ion batteries provide sufficient power for operation of the fully loaded logger for 6 hours. The EKG and EMG signals collected in the dynamic field test provide sufficient physiological data. The subject's heart rate peaked at roughly 180 bpm after each 100-m run and decreased gradually to 160 bmp during walking (Fig. 4). The EMG RMS value during the 100-m run was approximately 8.16-fold in the rectus femoris and 5.05-fold in the gastrocnamius of that during walking. The monitoring software plots the telemetered signals in a 4-channel waveform chart. Figure 5 shows a 5-sec waveform chart plotted at a monitoring rate of 100 samples/s/channel during the dynamic field test. The waveforms are the EKG signals, left rectus femoris EMG signals, and left gastrocnamius EMG signals for the subject at minute 5. Investigators monitored signal

waveforms during the test. However, some telemetered data loss was encountered when the logger transmission was obstructed by the subject.

In the prolonged field test, the logger successfully collected 4-hour consecutive EKG signals for an investigator. Figure 6 shows a 10-sec sample of recorded EKG waveforms and 4-hour heart rate history computed from the R-R interval of the adjacent QRS waveform. The EKG waveforms had a high signal/noise ratio and only contaminated by the small pectoral muscle EMG signals. The heart rate history was in accordance with the physical activities the investigator performed during the 4-hour test.

4. Discussion

One benefit of using wireless telemetry is providing flexibility and mobility by remov-

ing the need for a cable. Current communicaprotocols commonly utilized tion for short-range (10–100 m) wireless telemetry are Bluetooth, ultra-wide band (UWB), ZigBee, and Wi-Fi, which correspond to the IEEE 802.15.1, 802.15.3, 802.15.4, and 802.11a/bg standards, respectively. Several studies demonstrated the merits and shortcomings of these protocols in terms of capacity, security, network topology, power consumption, and quality of service (QoS) [14, 15]. Baker (2005) compared the strengths and weaknesses of ZigBee and Bluetooth technologies in industrial applications [16]. Baker claimed that ZigBee over the IEEE 802.15.4 protocol meet a wider range of industrial needs than Bluetooth due to its advantage of long-term battery operation, greater range, and higher flexibility and reliability for mesh networking architectures. Bluetooth has a higher data transmission rate than ZigBee; however, Bluetooth also consumes more power than ZigBee. Several bio-sensors have been developed for transmitting data over a ZigBee sensor network [10, 11]. For the field test, this study chose to use ZigBee for telemetry based on its low power consumption and high flexibility of mesh networking architectures. Therefore, the logger records data locally acquired by the built-in microcontroller, and can be modified to record data sent from remote ZigBee sensors.

This study demonstrates that as transmission distance increased, the accuracy of received data decreased. The indoor telemetric range of the ZigBee module is 90m according to the manufacture [17]. Nevertheless, a 2.4-GHz radio frequency signal emitted from the logger can be interfered with or blocked by the body of the person carrying the logger. Therefore, obtaining a high monitoring rate with the proposed system may not be easy for telemetry over a great distance. Some existing systems have utilized remote devices to record data from wireless sensors and lose data due to radio frequency interference [7]. The architecture of the proposed logger system eliminates data loss while providing the capability of telemetric monitoring. The reduced monitoring rate caused by increased transmission distance can be improved by increasing transmission power, using a high-gain antenna, or relocating the receiver. For field tests and real-time waveform monitoring, a feasible way of obtaining a adequate monitoring rate is to use a small omnidirectional antenna for the logger and a large directional antenna for the receiver. Nevertheless, selection of antenna gain must consider radio exposure of the person carrying the logger.

Durability is essential for battery-powered data-acquisition systems. System durability is determined by battery capacity, data storage size, and power consumption rate. A data logger with good durability can operate consecutively without a need to replace batteries or storage media. The proposed logger uses a microSD or microSDHC card as the storage media; both are small in size, lightweight, consume little power (15mA), and have a high storage capacity (up to 16G-Byte). A regular 2G-Byte microSD can hold data for up to 45 hours from the logger at a 1000-Hz sampling rate. The operating current of the ZigBee module is approximately 55mA when receiving data and 250mA when transmitting data. By using 860mAh batteries, the logger can operate continually for 6 hours at a modmonitoring rate of 250 erate samples/s/channel. However, logger temperature increases as power is consumed. According to investigator experience, temperature of the fully loaded logger can increase to 40°C when carried on a person's belt, and to 45°C when carried in a pocket. This temperature can cause subject irritation in hot climates. Therefore, an effective way of saving power is to reduce the rate of data telemetry when a high monitoring rate is not required.

Laboratory and field tests demonstrate that the proposed data logger, together with the associated monitoring system, is an effective tool for measuring worker physical workload.

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Figure 5. Screen shot of the monitoring software, which shows 5-sec telemetered EKG (channel 1), rectus femoris EMG (channel 2), and gastrocnamius EMG (channel 3) signals at a monitoring rate of 100 samples/s/channel.



Figure 6. EKG and heart rate recording of a participant during a 4-h prolonged field test.

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