135-Hour-Battery-Life Skin Temperature Monitoring System Using a Bluetooth Cellular Phone

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***Abstract* — In this paper we present a long-term temperature monitoring system that uses miniature wearable sensor nodes that connect via Bluetooth to a cellular phone in a star topology. Monitoring of skin temperature over multiple days has been shown to be useful in clinical research related to metabolic and cardiovascular diseases, and it has a potential role in the study of circadian rhythms in patients with cancer. The system can provide immediate remote feedback through a phone's internet connectivity and eliminates the need for a dedicated base station. By utilizing Bluetooth in a burst-mode regime, sensor nodes can work autonomously for 135 hours at a sampling rate of 0.2 Hz. A validation study showed that the system can reliably record circadian temperature rhythms in an ambulatory environment, and can serve as a sensor platform for novel applications.**

***Index Terms* — Telemedicine, Bluetooth, biomedical telemetry, body sensor networks, circadian rhythm.**

I. INTRODUCTION

Recent research has shown that multiple-day continuous monitoring of skin temperature can provide clinical and research insights, such as to distinguish ultradian and circadian rhythms that can be useful in optimizing the timing of chemotherapy delivery for cancer [1]. Also, continuous temperature recoding has been used to study brown fat thermogenesis, which might lead to a better understanding and treatment of obesity [2], and to study biomarkers for vascular function in patients with sickle cell anemia [3]. However, we found that the current technologies for long-term temperature monitoring in multiple skin areas are not suitable for many clinical studies, which led us to develop a new system for skin temperature monitoring.

Commercial wearable data loggers, such as iButton [4], cannot provide immediate temperature data to a remote location. Also, the current wireless nodes, such as VitalSense [5], require a bulky base station, which is uncomfortable to wear and, in our experience, is often mislaid by patients.

We designed a monitoring system where sensor nodes communicate to a cellular phone to provide immediate feedback to the clinicians who can then monitor long-term data collection remotely. Since a phone is an essential item for many patients, it is often taken everywhere; therefore it is unlikely to be forgotten, and it removes the need for a separate base station. To make the sensor system comfortable and non-obtrusive, it is critical to keep the phone functional for calling, web browsing, etc. while data are collected, and to reduce the impact of the sensor system on the phone's battery life. Since several sensor nodes, each measuring skin and ambient temperatures, are expected be worn by a patient for an extended period, on a single charge, the balance between long battery life and small size of wearable electronics, while maintaining data integrity and having a small data profile, should be considered. The system presented in this paper meets the above stated criteria, while overcoming obstacles presented by the high energy consumption of Bluetooth and the limited memory resources of the node.

The designed system achieves longer battery life than the iButton (48 hours battery at 1 Hz sampling), but not the VitalSense (10 days at 0.067 Hz), and achieves compatible current consumption to a research device [6], which we estimated at 0.83 mA at 1 Hz sampling.

TABLE I

NODE SPECS AT 0.2 HZ SAMPLING RATE, 3.0 V SUPPLY

Skin micro thermistor specs.	Resolution	0.008 °C
	Accuracy	± 0.115 °C
	Range	29 to 37 °C
Ambient sensor specs.	Resolution	0.0625 °C
	Accuracy	± 0.5 °C
	Range	-55 to + 125 °C
Power Estimates	Bluetooth on	47 mA (141 mW)
	Bluetooth off	0.73 mA (2.19 mW)
	Average	0.82 mA (2.46 mW)
	Battery life	135 hours
Wireless specs.	Range	Max 10 m
	Wireless protocol	Bluetooth Class II 2.4 GHz

II. SYSTEM DESIGN

A. Sensor Node Design

The design specifications of the sensor node at a 0.2 Hz sampling rate are given in Table 1. Each node is based around a microcontroller (ATmega328, Atmel). Individual nodes are powered by a 110 mA 3.7 V lithium polymer battery at a regulated 3.0 V supply. A Serial Port Profile

(SPP) is used by the on-board Bluetooth module (RN-42, Roving Networks) to transmit raw data from the microcontroller to the phone. Skin temperature is measured with a micro thermistor (QTMB-14B3, Quality Thermistors) with a small mass that allows for a rapid thermal response. The thermistor is placed in a Wheatstone bridge circuit, to increase thermal resolution in a given skin temperature range. The bridge's differential output signal is amplified by an instrumentation amplifier and digitized by an analog-to-digital converter (ADC). The amplifier's gain and the bridge's zero resistance are dynamically adjusted by an on-board digital potentiometer. To prevent self-heating errors, the thermistor excitation current is limited to 20 μA. The thermistor was calibrated in a circulating water bath with a five-point linear calibration curve ($r^2 > 0.99$) in the 29 °C to 37 °C range. A factory-calibrated digital sensor (DS18B20, Maxim) transmits ambient temperature to the microcontroller through a 1-Wire interface.

As seen in Fig. 1 the sensor node is encapsulated in a custom plastic enclosure to protect the electronics from moisture and mechanical damage. The node attaches to the forearm by a custom-made Lycra wristband as shown in Fig. 1D or medical tape. The micro thermistor is secured to the skin with a piece of medical tape.

B. Cellular Phone

Custom software for an Android OS phone (G2, HTC) allows the user to save data to a 16 GB micro SD card and use a cellular network to transmit data to an external server or e-mail account. The phone was programmed to notify the user by vibrating if a connection with a sensor node fails. For security purposes, a pairing key was needed to initially connect the phone to a given node. The phone can connect to multiple senor nodes, but for the purposes of this paper, we will consider a one to one connection between the phone and a node.

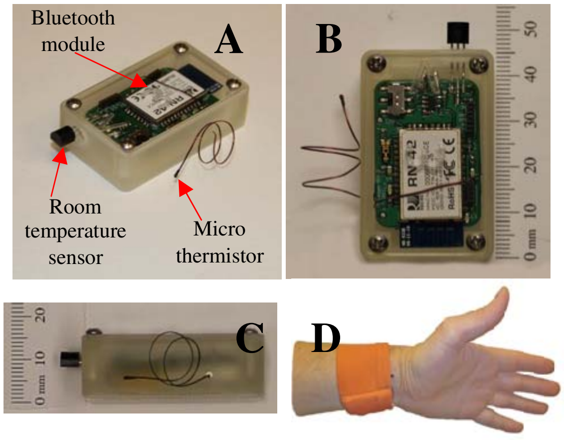

Fig. 1. (A) Sensor node inside a plastic case and covered on top with a clear PETG lid; (B) Top view of the node with ruler (in mm); (C) Side view of the node with a ruler; (D) node is worn on a wrist and hidden inside orange wristband.

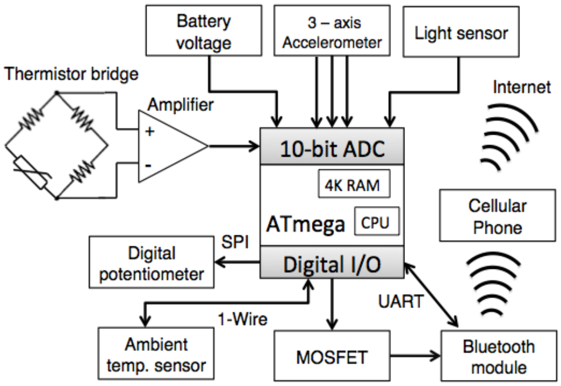

Fig. 2. System block diagram. (Note: the accelerometer and light sensor are present on the hardware, but not discussed in this paper)

III. LOW POWER OPTIMIZATION

A. Burst Bluetooth Communications

Node current consumption was 47mA with Bluetooth *on*, and 0.73 mA with Bluetooth *off*. A sensor node's battery lasts 2 hours during continuous transmission. Therefore using Bluetooth in periodic bursts was the primary strategy to increase battery life.

When first turned *on*, a sensor node waits for a Bluetooth connection from the master phone, which is necessary to synchronize the two devices. A successful connection event causes the node to turn *off* its Bluetooth module with a power MOSFET, and activates skin and ambient temperatures logging to the allocated 960 bytes of RAM in the microcontroller. Also, the microcontroller enters a low-power mode (0.73 mA current draw) by decreasing its clock to 250 kHz. When the memory is full, the Bluetooth module is switched *on*, and microcontroller clock is increased to 8 MHz. Concurrently, the phone software timer wakes up the phone to initiate a Bluetooth connection, receive the data, and store the data. After establishing the connection between the node and the phone, collected data are transmitted in a burst. After the burst is completed, the node's Bluetooth module is turned *off*, and the cycle repeats. To avoid losing new data in case the node's memory is full and a Bluetooth connection attempt to send previous data fails, new data are placed into 400-byte buffer, while more connection attempts are made.

B. Power Consumption Measurements

As shown in Fig. 3, we measured the effect of skin temperature sampling rate on power consumption of the sensor node and determined that expected battery life can vary from 20 hours (at 25 Hz) to 135 hours (at 0.2 Hz), depending on the sampling rate. At a low sampling rate the energy consumption of microcontroller dominates, while at a high sampling rate the Bluetooth module's energy consumption dominates.

The phone current was 55 mA when idle and 104 mA (at 3.3 V) while receiving Bluetooth data.

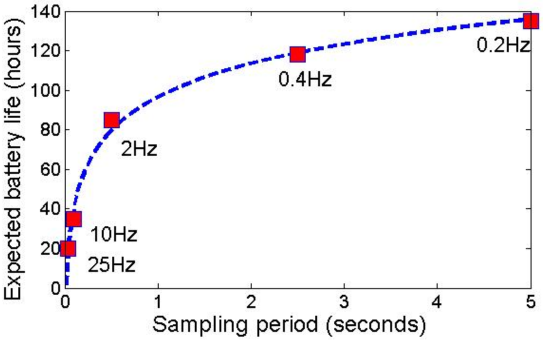

Fig. 3. Battery life of a sensor node at different temperature sampling periods. Dashed line represents logarithmic fit. The squares represent the battery life at a specific frequency.

IV. CIRCADIAN RHYTHM VALIDATION

A 23-year-old healthy volunteer wore the sensor node over a period of 48 hours, outside of the lab. The volunteer kept a log journal to record the times at which activities such as sleeping and eating were performed. The sampling rate was 2 Hz. As seen in Fig. 4, the data show the increase in the skin temperature during onset of sleep, which is characteristic of circadian rhythm [7]. The flat lines at 28.5 °C correspond to the times the node was removed intentionally. The connections were reliable: no data were lost, and the system was fully autonomous. Also, data collection did not interfere with the phone's other functions, such as calling and Internet browsing.

V. CONCLUSION

In this paper we developed a system to study long-term skin temperature fluctuations in an ambulatory environment. We demonstrate that an Android OS cellular phone can be used as a data receiver for low-power sensor nodes. Future sensor nodes may include a 3-axis accelerometer and light sensor to enable additional functionality, such as activity monitoring or fall detection.

We are exploring the use of epidermal [8] and flexible circuits to further miniaturize the sensor nodes, so that they can be comfortably worn on any parts of the body. Currently, the sensor system is in use in clinical trials at the National Institutes of Health to better understand the reliability, comfort, and value of the system.

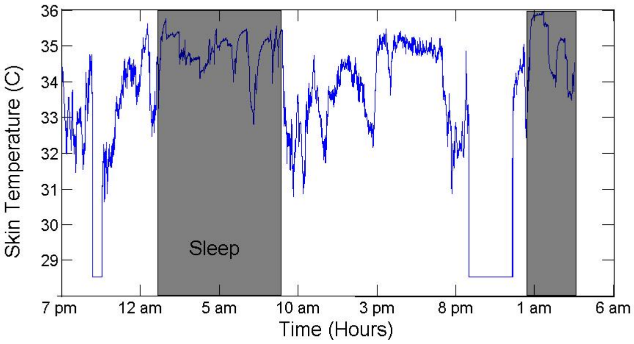

Fig. 4. Temperature fluctuations observed over 33 hour period in habitual environment. Shaded regions represent time in bed.

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