Wireless System for Continuous Monitoring of Core Body Temperature

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***Abstract*—A wireless wearable device aimed at continuously monitoring internal temperature a few centimeters deep in the body is presented. A radiometer operating in the 1.4-1.427 GHz quiet band is used with a circular patch probe to measure the thermal radiation emitted by the body, which is proportional to temperature. The output is digitized and transmitted over Bluetooth by a TI CC2541. The wearable device is powered by a 3.7 V Li-Ion battery, through three buck-conversion circuits. The sensor design trades performance (continuous calibration) for simplicity to reduce size and power consumption. Validated measurement data of water temperature inside the cheek demonstrates the feasibility of radiometric internal temperature measurement in a wearable platform.**

***Index Terms*—Wearable, Bluetooth, Internal Temperature, Healthcare, Radiometry, Thermal Radiation**

I. Introduction

Improvements in technology and increased public interest in health and fitness are driving rapid growth in wearable electronics. Mature products such as fitness watches from Fitbit Inc. (San Francisco, CA) and chest straps from Wahoo Fitness (Atlanta, GA) feature wireless connectivity and track metrics including heart rate, number of steps taken, and activity during sleep. The newly released MyoWare sensor from Advancer Technologies LLC (Raleigh, NC) measures muscle activation and allows rapid prototyping of wearable devices that make use of electromyography. Other non-invasive sensing techniques are under active research, such as Doppler Radar for detecting blood pressure [1], photoacoustic spectroscopy for measuring blood glucose levels [2], and radiometry for tracking core body temperature [3].

Although there are a number of ways to track internal body temperature, most are invasive (e.g. rectal probes), or large and expensive, such as MRI. Heat flux thermometers are compact but have limited depth resolution [4]. An alternative method based on microwave radiometry was attempted by several groups, e.g. [3], [5], [6], [7], and [8]. Most of these are not wearable and are focused on broadband operation in order to integrate as much noise power as possible. For many applications, such as monitoring athletes, soldiers and emergency personnel under heavy training, continuous measurements of core body temperature are essential and there is no current non-invasive wearable solution. Other important applications include monitoring internal temperature during sleep studies, monitoring patients under recovery and monitoring temperature of tissues during hyperthermia and other treatments.

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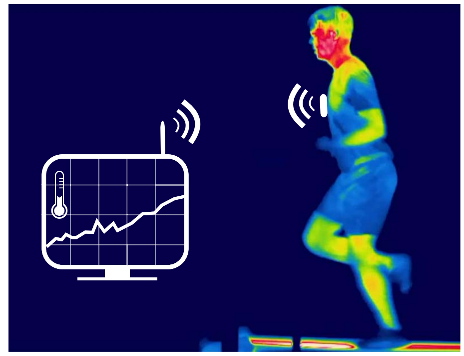

Fig. 1. Illustration of wearable wireless microwave thermometer operation, where black-body radiation is measured by the wearable device and transmitted wirelessly to a computer for temperature retrieval and logging. The FLIR camera example infrared image is published by Buzzfeed.

The goal of the research presented here is to demonstrate a wearable wireless microwave thermometer, as illustrated in Fig. 1, capable of real-time noninvasive monitoring of core body temperature. A probe placed on the skin receives black-body radiation from all tissue stacks under it, and this total power is fed to a low-noise microwave receiver. The knowledge of the near-field profile in the tissues under the probe, obtained from full-wave simulations, is used to estimate the temperature of a specific buried layer. Although the peak of the black-body radiation for humans is in the infrared portion of the electromagnetic spectrum, IR does not penetrate more than about a millimeter and is therefore only useful for radiometric measurements of the skin temperature. Lower GHz frequencies correspond to multiple centimeter penetration depth, but much less power.

II. Wearable Wireless Sensor Architecture

The overall architecture of the wearable microwave thermometer is shown in Fig. 2. The probe and radiometer are designed for operation in the quiet band allocated to radioastronomy at 1.4 GHz in order to minimize RFI from the environment and for penetration. A thermistor is included for independent temperature measurements in accessible areas, e.g. on the skin or inside the mouth. The output of the radiometer is a DC voltage which is ideally linearly proportional to received power, and therefore temperature ($P = kTB$). This voltage is digitized (12-bit) and time-averaged (over 1000 samples) inside the TI CC2541, a low-power 2.4-GHz transceiver integrated with a low-power micro-controller (MCU). The data can then be transmitted via a low-energy Bluetooth link from a inverted-F antenna printed on the PCB. The integrated MCU and TX/RX enable very low

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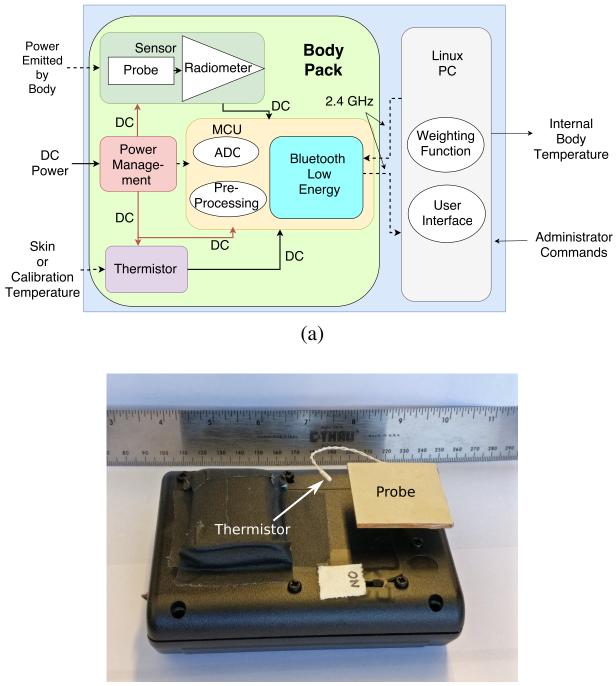

(a)

(b)

Fig. 2. Functional decomposition of the wearable device (a), showing the organization of subsystems, and photograph (b) of the wearable device.

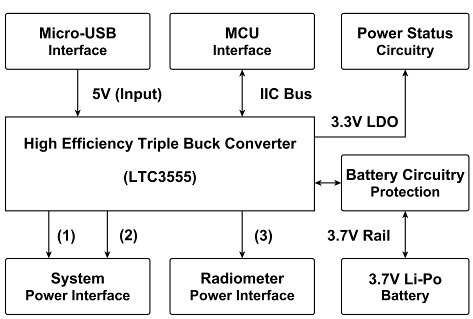

Fig. 3. Block diagram of triple-buck power delivery and battery management system for the wearable device. (1), (2) and (3) refer to the output voltages V_{B1}, V_{B2}, V_{B3} from Fig. 4.

standby power consumption and a smaller and simpler circuit. The transmitted data is received by any Bluetooth 4.0 receiver and processed to estimate and track tissue temperature, and the data processing is mostly done externally in order to maximize battery life of the wireless platform. The MCU also controls the power for all the components.

The power management unit is essential for operation of the wearable device, one of the challenges being that the radiometer requires an extremely clean 3.3-V supply. The other challenge is a separate reference voltage required for the ADC which also needs to be low-noise. Additionally, efficiency should be as high as possible. A 3.7-V Li-Ion battery is the main storage element, charged by a 5-V USB unit. The LTC3555 triple-buck converter provides the different required voltages along with the three feedback loops shown in Fig. 4.

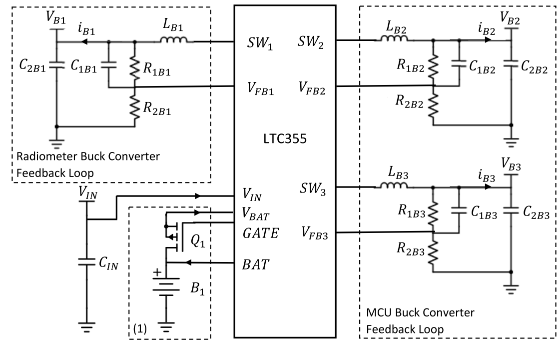

Fig. 4. Schematic of LTC355-based triple-buck voltage generation circuit used to power the radiometer as well as the digital and wireless components of the wearable device from a lithium-ion battery.

III. RF Subsystem

The RF sub-system consists of a probe placed on the surface of the body, and a low-noise microwave receiver with a block diagram as shown in Fig. 5. The components are off-the-shelf low-noise amplifiers (TriQuint TQP3M9037) and filters (Minicircuits CBP-1400E+). The noise figure is calculated to be 0.48 dB with a gain of 32.2 dB. For the measurements presented in this work, the switch and noise sources of a standard Dicke-type radiometer [9] are not present, but can be added for improved calibration. In the wearable device presented here, a thermistor is used to independently measure temperature that calibrates the radiometer, which is a short-term calibration and needs to be repeated for each measurement. While this method is simpler, consumes less power and allows for a lower noise figure since it does not have a switch, if longer-term continuous calibration is needed, the wearable device can incorporate hot and cold noise sources for a Dicke architecture. Fig. 6 shows measured data that illustrates this tradeoff. The plot shows the measured uncalibrated receiver gain over 80 minutes and the gain when a single cold noise source is used with a switch. With just the thermistor, the gain is maintained over approximately 1 minute.

The frequency chosen for measuring temperature is 1.4 GHz since the penetration depth in most tissues is several centimeters. While a lower frequency would give more penetration, the probe size needs to remain small for a wearable device and was a trade-off parameter. A significant challenge in black-body power measurements is the extremely low power (in the -100 dBm range) which makes even low-level RF interferance problematic. The 1.4-1.427 GHz quiet band helps this problem, but implies a narrowband receiver, which requires longer integration time. Therefore, the probe, filters, LNA and diode detector cascade is designed for a 27-MHz bandwidth, where for size and cost constraints the probe and detector are designed in-house and have the narrowest bandwidth.

Fig. 5 shows a sketch of the probe cross-section (only the superstrate which contacts the body is shown in the photo of Fig. 2). The probe is a near-field circular patch antenna with a high-permittivity superstrate that provides impedance matching to the tissues layers with electrical properties given

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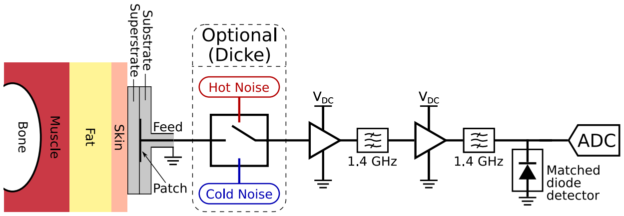

Fig. 5. Schematic of the RF receiver, showing optional noise sources and switch that can be added to implement a Dicke radiometer for gain variation calibration. A near-field antenna probe is in contact with the skin ($\epsilon_r = 39.7, \sigma = 1.04$ S/m) over a layer of fat ($\epsilon_r = 11.2, \sigma = 0.150$ S/m), muscle ($\epsilon_r = 54.1, \sigma = 11.4$ S/m) and bone ($\epsilon_r = 12.1, \sigma = 0.211$ S/m) [11], where the layers depend on the body part and the values are given for 1.4 GHz.

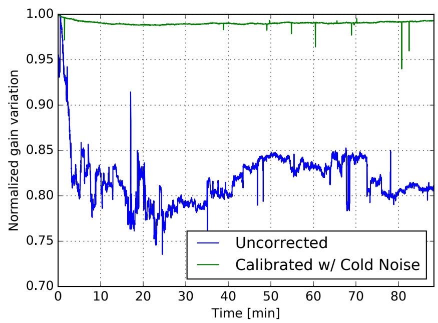

Fig. 6. Measured uncalibrated receiver gain over time and the gain when a single cold noise source is used with a switch. With just the thermistor (Fig. 2), the gain is maintained over approximately 1 minute.

in Fig. 5 caption. The probe is designed using HFSS to maximize reception from internal layers [10].

IV. Measurement Results

Measurements are performed on the cheek since the internal temperature can be independently verified and controlled with water of different temperatures. The wireless sensor is positioned as shown in Fig. 7 and transmits temperature data to a Bluetooth receiver of computer. The temperature is instantaneously displayed after applying the calibration with the temperature previously measured with the thermistor. An example measurement is shown in Fig. 8, where the radiometer was calibrated with room-temperature water before measuring hot and cold water in the mouth. For this measurement, the thermistor is placed in the mouth to directly measure the water temperature as independent verification of the radiometer measurement. While there is also thermal conduction through the cheek, the time constant is very slow compared to the scale in Fig. 8 since black-body radiation propagates at the speed of light through tissues. It is seen that the wearable wireless microwave thermometer can track the temperature changes through tissue layers, which is sufficient for a number of monitoring applications. This proof-of-concept wearable wireless device can be further dramatically miniaturized with monolithic integration.

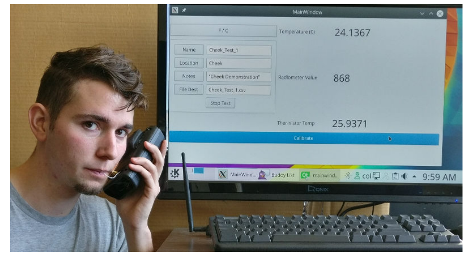

Fig. 7. Demonstration of device placement on the body for measurements, on the cheek to enable independent temperature verification. A chest strap may be used for core-body measurements through the sternum.

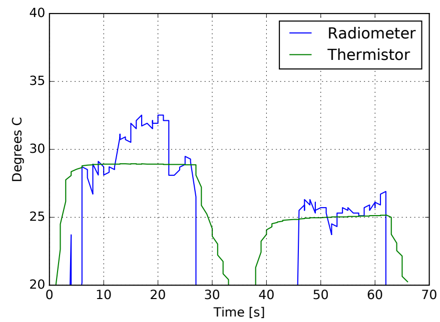

Fig. 8. In vivo measurement of water with different temperatures inside a human cheek (for verification), performed simultaneously with a thermistor inside the cheek and the wearable device outside.

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