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MEASUREMENT OF ECG, RESPIRATORY RATE, TILT AND TEMPERATURE OF A PATIENT AND WIRELESS ZIGBEE DATA TRANSMISSION

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ABSTRACT

A wireless sensor belt, designed as a mobile monitoring device for hospital use, was built during the work reported here. This sensor belt is capable of measuring electrocardiogram (ECG), respiratory rate, tilt and skin temperature. Its analogue electronics were designed to be effective, have a low current consumption and use the most suitable components available for all couplings.

For wireless data transmission, the sensor belt utilizes a separate module, attached to a base soldered to an analogue electronic PCB (Printed Circuit Board). On this module, there is an 8051 microcontroller and a ZigBee transceiver supporting the IEEE 802.15.4 standard. Programming of the module was done in the Linux environment using the C language.

The sensor belt proved capable of successfully sending wireless data. Moreover, wirelessness improved signal quality, as it reduced the noise coupling risk. This effect could be observed in the quality of both ECG and accelerometer signals. Among the greatest benefits of wirelessness is increased mobility. To sum up, the capacity to receive a large amount of measurement data from the belt and the application of new wireless data transmission based on ZigBee technology make the sensor belt a remarkable application for the needs of the wireless hospital.

I. INTRODUCTION

Wirelessness is becoming increasingly popular in healthcare and biomedical engineering. Pre-pilot projects conducted under the banner of the Wireless Hospital project[1] (WILHO) by the University of Oulu in cooperation with local hospitals and other partners have demonstrated that there is a pressing need for mobile devices capable of continuously monitoring patient status [1]. One of the projects involved the development of a sensor belt for measuring vital parameters of the human body 24 hours a day, while allowing the user to move around without any wires. This requires continuous wireless data transmission, enabled by an extensive radio network.

Designed for hospital use, the sensor belt is part of a bigger system comprising, in addition to the belt itself, hubs in each room and hallway as well as a server located in an office. All data are transmitted wirelessly from the sensor belt to a hub, which then forwards the data to the server via the Ethernet. The server then saves important data in the hospital database.

Patient identification has been considered as an important issue in the wireless hospital project. An ID-Beacon device was therefore developed to read ID-tags attached to medical devices, patients and nurses, connecting them together in a network. It also forwards data wirelessly from the medical devices to the hubs. Also the sensor belt has an ID tag and is regarded as a medical device by the system, although it sends its data by itself.

The measurement system used in the laboratory tests described here consists of a sensor belt, a receiver connected to a computer and software to handle and display incoming data.

II. SYSTEM AND HARDWARE

A. Devices

Fig. 1 illustrates the different components of the measurement system.

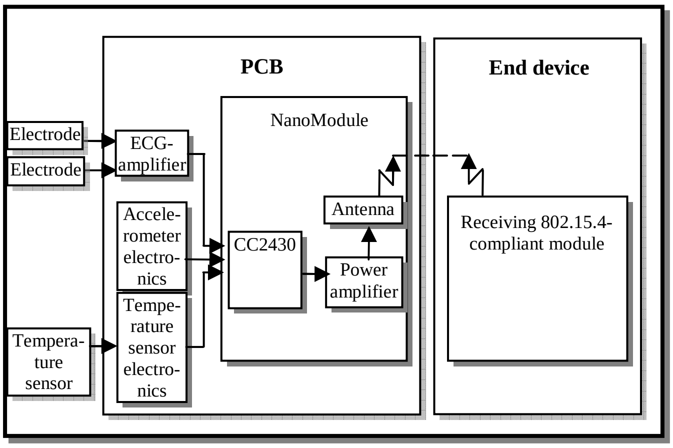

Figure 1: Measurement system.

Measurement data from the sensors on the belt are transferred wirelessly using the NanoModule by Sensinode Ltd [2], which has an 802.15.4 radio. A module on the receiving side, equipped with a similar radio, receives the signals, which are then forwarded to the serial port of the PC for further processing.

1) Sensor belt

Integrated within the sensor belt are two ECG electrodes. Signals from the electrodes are amplified with a gain of 300 (24.8 dB) and filtered with the cut-off frequencies of 0.05 Hz and 123 Hz. The amplifier circuit has an AC front end [3]. Amplification and filtering are done in two stages.

[1] http://www.wilho.net

Each patient's respiratory rate and tilt are measured by a 3-axis analogue accelerometer MMA7260QT [4] from Freescale Semiconductors. Both amplified and unamplified accelerometer signals are fed to the microcontroller. Unamplified signals are particularly important for the tilt measurements, where the amount of tilt is determined from the signals' DC level. Amplification with one-sided supply voltage amplifiers sets the level to the middle of the amplifier's dynamic range. Respiratory rate, on the other hand, is measured from the acceleration caused by the movement of the solar plexus, which gives the best signal and the most reliable test results [5].

Temperature measurements are made by a NTC-type R-T-curve matched sensor. This sensor is attached to the belt and measures therefore skin temperature. Fig. 2. shows the system used in the measurements.

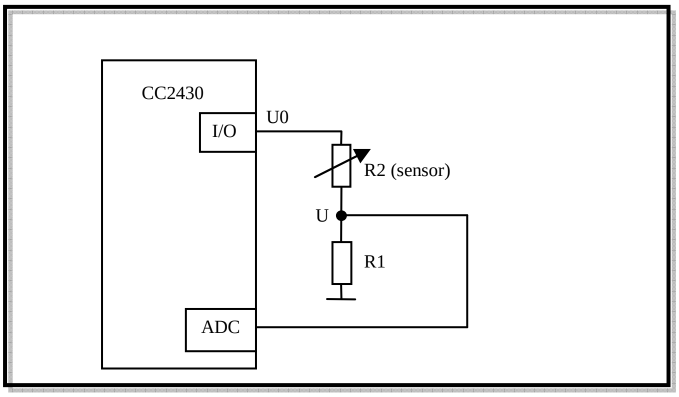

Figure 2: Temperature measurement system.

Temperature measurements can be made with a resistance sensor so that a serial connection is made between the sensor and a resistor, whose other end must be connected to ground. The other end of the sensor is connected to the microcontroller's digital I/O-port. When the port is set to "high" stage, its voltage rises to 3 V. A voltage division appears between the sensor and the resistor, where the voltage can be read by the AD converter. The voltage at the voltage division point can be measured using equation

$$U = (R1/(R1+R2))xU0\,, \qquad (1)$$

where *U* is the voltage read by the AD converter, *U0* is 3 V, *R2* is the resistance of the sensor and *R1* is a known resistance value. The voltage given by the equation corresponds to the resistance change in the temperature sensor caused by a temperature change in it.

2) Receiving module

The receiving module is a Micro USB module from Sensinode Ltd. [2], which has two boards attached to each other. One of the boards contains a MSP430 microcontroller and a CC2420 ZigBee transceiver, while the other one comprises components enabling a USB connection. As a result, it is possible to connect the module to a PC via a USB cable and program the board to forward incoming data to the PC's USB port.

3) PC software

Incoming data are handled in the computer using LabVIEW software to read the data packets and find the data bytes which contain measurement information. These are utilized to plot a graph and/or display such parameters as pulse or respiratory rate.

B. Wireless communication

Data communication between the sensor belt and the receiving module is accomplished following the 802.15.4 standard radios as shown in Fig. 3.

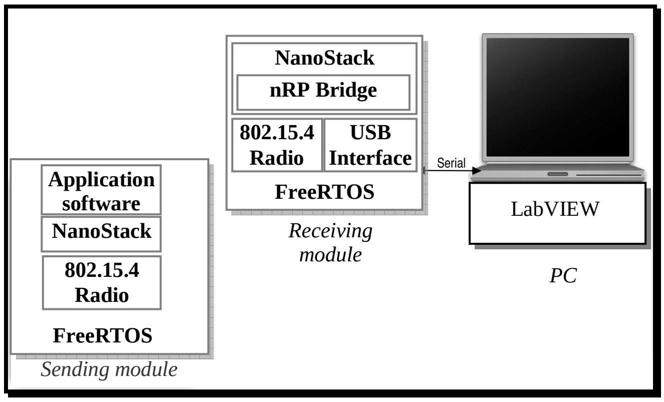

Figure 3: Components used in data transmission.

1) 802.15.4

IEEE 802.15.4 is a radio transmission standard intended for wireless low data rate transmissions over small distances [6]. Published in the summer of 2003, the standard is based on the OSI protocol model, which is widely used as a reference for layered protocols. The standard defines only the two lowest layers; namely, the physical and MAC layers. On top of these, the ZigBee Alliance has developed the so-called ZigBee specification, containing network and application layers. Together, the standard and specification form an application generally referred to as ZigBee.

The ZigBee technique enables cheap and easy development of a virtually unlimited number of wireless low rate monitoring and controlling devices. This contrasts with both Bluetooth and WLAN, which only allow a limited, low number of network nodes. Moreover, compared to ZigBee, these techniques are fairly complicated. ZigBee has very low latency when connecting to a network (30 ms) and starting communication (15 ms). However, since ZigBee's data transmission rate is quite low (250 kb/s) compared to the other techniques, it is best suited for the transmission of text and sample data. ZigBee applications can be used in many technical fields, including industrial monitoring and control, home automation, sensor networks, biomedical engineering and auto manufacturing [7, 8].

ZigBee uses the same unlicensed 2.4 GHz (worldwide), 868 MHz (Europe) and 915 MHz (USA) radio channels as many wireless phones. At 2.4 GHz, data transmission distances vary from 70 meters to 300 meters.

Two different variations of the technology can be found: the slotted and the unslotted channel structure.

The slotted channel structure uses synchronization between devices enabled by beacon exchanges and a slotted CSMA/CA mechanism as described in [9]. When a device wishes to send data frames, it waits for a random number of slots. Then, medium idleness is evaluated during a CCA (Clear Channel Assessment) period of time. If the medium is still idle at the end of this period, the packet can be sent at the beginning of the next time slot, otherwise the procedure is restarted from the beginning.

In the unslotted channel structure, if a device wishes to send data frames, it waits for a random period of time. Then, if the medium is still idle after a CCA period of time, the frame transmission can start.

The physical layer describes three different frequency bands:

-1 channel in the (868 to 868.6) MHz band, providing 20 kbps.

-10 channels in the (902 to 928) MHz band, providing 40 kbps each.

-16 channels in the (2400 to 2483.5) MHz band, providing 250 kpbs each.

We focus our effort on the unslotted version in the 2450 MHz band as it provides the highest data rate combined with the least overhead (i.e., no beacon frames).

2) NanoStack

Application software is built on top of NanoStack [2] which uses FreeRTOS[2] for real time operation. Software architecture consists of the Nanostack protocol solution for embedded wireless nodes, along with drivers and tools for accessing wireless nodes from a PC. Nanostack is an advanced open-source protocol stack solution with IP over IEEE 802.15.4 (6LoWPAN). It is executed as a single task in the FreeRTOS environment. This allows reduced RAM usage and provides an effective way of flow control, since protocol modules are always executed sequentially. Stack usage analysis is also simplified, as the protocol modules do not use direct function calls between each other. The main stack loop is responsible for module handler execution. Buffers move along a single buffer queue, which ensures that the user application is not blocked during protocol stack operation.

III. TESTS AND RESULTS

System tests were conducted in two stages. First, signal quality was tested using a wired setup to enable comparison with wireless signal quality. Among the tested variables was noise filtering. The second stage included temperature sensor tests, accelerometer tests both with and without amplification as well as filtering and tilt measurement tests.

1) Wired tests

Wired tests were made by connecting signals to an analogue/digital measurement card manufactured by National Instruments and using the LabVIEW program to read them. The program read samples of the signals and plotted them on a graph on the PC screen.

Fig. 4. shows a wired ECG signal. As evidenced by low amplitude noise, signal quality was fairly good.

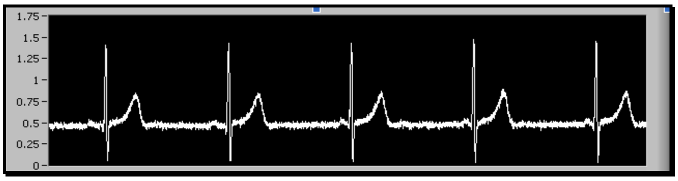

Figure 4: Wired ECG signal.

Accelerometer tests showed that a gain of 7 (8.5 dB) is too small for detecting the very small solar plexus movements of a sleeping patient. So the gain was increased to 21 (13.2 dB). This, however, made it impossible to measure the respiratory rate of a moving patient, whose steps produced high voltage peaks which saturated the amplifiers. Thus, the AD converter must be accurate enough to measure signals that are either unamplified or very little amplified.

2) Wireless tests

One purpose of the wireless tests was to establish the accuracy rate of the microcontroller's 14-bit AD converter, and to determine if respiratory rate measurements necessitate amplification. One central finding was that amplification is not necessary for accurate results. In addition, these tests gave good information about the effects of wireless transmission on signal quality. These tests focused on ECG, respiratory rate, tilt and temperature.

As Fig. 5 illustrates, the quality of wireless ECG signals was very good.

Figure 5: Wireless ECG signal.

Usually, two-point ECG measurements require a third grounding electrode to set the patient and the measurement system to the same potential level, but this is not necessary in wireless measurements. A wireless device is not connected by

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[2] http://www.freertos.org/

wires to any particular potential level, thereby enabling measurements on patients regardless of their electronic potential. Because a third electrode is not needed, ECG can be measured using only the belt with its integrated electrodes. This makes the measurements user-friendly.

Wirelessness was found to minimize the possibility of noise being coupled to the signal. In addition, the 8-bit resolution used in the ECG measurements proved sufficiently accurate.

Accelerometer tests included measurements of respiratory rate and tilt. Respiratory rate measurements demonstrated that the accuracy offered by the AD converter's 14-bit resolution was good enough for measuring unamplified accelerometer signals. The waveform produced by normal breathing can be seen in Fig. 6.

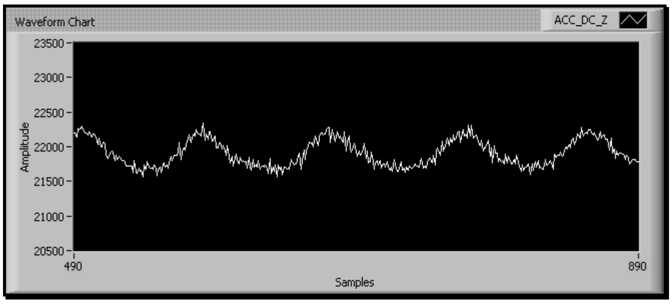

Figure 6: Acceleration on Z-axis in normal breathing.

As the measurements were made with the belt's case partly on the solar plexus, the accelerometer swung back and forth. A change in the gravity of the accelerometer's Z-axis produced a corresponding waveform change. Outputs of the other axes can be used to measure the respiratory rate when the patient is not standing or sitting straightforward. This is made visible by the variation in the DC level, as shown in the figure.

Fig. 7. shows the accelerometer's output in a tilt measurement when the accelerometer is turned 90° and back.

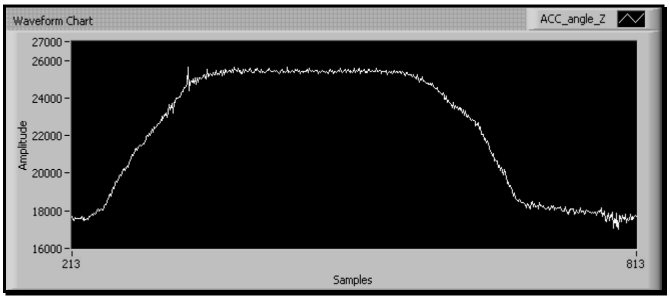

Figure 7: DC level change when turning the accelerometer 90° and back.

Tests performed on the temperature sensor proved that it is possible to measure temperature with the required 0.1 °C accuracy, as demonstrated by Fig. 8. Shown in the figure is the change in voltage which occurs when the sensor's temperature changes from air temperature to skin temperature (skin contact). Each voltage value is related to absolute temperature.

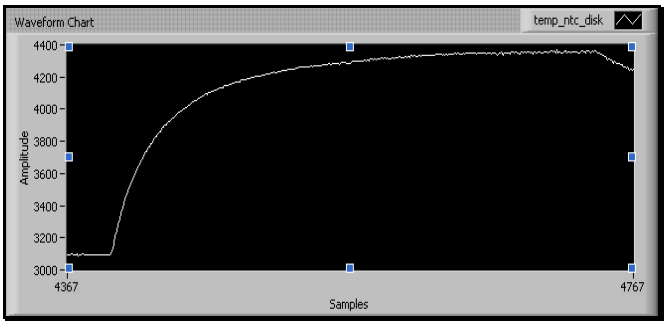

Figure 8: Voltage change caused by the temperature sensor in skin contact.

Some important test results can be summarized as follows. First, 8-bit resolution is enough when measuring ECG. However, 14-bit resolution must be used when measuring respiratory rate, tilt and temperature. Further, the resolution provided by the microcontroller's own AD converter is sufficient for measurements on respiratory rate using unamplified accelerometer signals. Yet another significant finding is that wirelessness improves signal quality. And finally, respiratory rate measurement based on DC level variation is possible and actually gives a better signal than an AC coupled measurement.

The sensor belt under tests is presented in Fig. 9.

Figure 9: Sensor belt.

IV. Conclusions

This paper presents a wireless sensor belt that is used to measure several vital health parameters. For data transmission, this device uses ZigBee technology, which is a new radio technology that is well suited for transmitting small amounts of data, such as data samples. Its greatest benefits are simplicity of structure, low latency time, low current consumption and a virtually unlimited number of network nodes.

The aim of this work was to develop a mobile wireless sensor belt for hospital use. Main users would be patients on the in-patient ward, whose health condition could be easily and comfortably monitored with this belt. If attached to patients as they entered the hospital, the device would extend monitoring time to cover their entire stay at the hospital.

Current work on the sensor belt focuses on programming, especially on calculating pulses from ECG signals and respiratory rate from accelerometer signals.

This sensor belt has several advantages which make it well suitable for the needs of the wireless hospital. It provides information on several of the most important health parameters. It gives freedom for the patient to move around in the hospital while being monitored. It also utilizes ZigBee radio technology, which has many superior qualities compared to current technologies such as Bluetooth and WLAN.

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