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The Ring Sensor: a New Ambulatory Wearable Sensor for Twenty-Four Hour Patient Monitoring

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Abstract This paper describes the development of a ring sensor for twenty-four hour patient monitoring. The ring is packed with LEDs and photo detectors where the technology of pulse oximetry is implemented for blood oxygen saturation monitoring. The measured data are transmitted to a computer through a digital wireless communication link. The ring sensor is worn by the patient at all times, hence the health status is monitored 24 hours a day. Detailed descriptions of the hardware and the software of the ring sensor will be presented. Also, the effects of motion artifact and ambient light will be investigated.

1. Introduction

As the population of aged people increases, close and continuous monitoring becomes more important. Real-time, continuous monitoring would allow not only for emergency detection but also for long-term assessment to establish the right dose and timing of medication. Especially, an ambulatory system that would allow long-term monitoring of otherwise difficult and noncompliant patients such as demented elderly people is highly in demand. A couple of compact, continuous monitoring devices have been developed [1-2] for elderly care. However, these devices have not been widely accepted due to the lack of functionality and comfort for wearers.

To answer these needs, we have developed a compact, non-obtrusive telemeterd wearable patient-monitoring device in a ring configuration. Figure 1 shows a photograph of the miniaturized ring sensor. This sensor is equipped with optoelectric components that allow for long-term monitoring of the patient's arterial blood volume waveforms and blood oxygen saturation non-invasively and continuously [3-4]. These signals are transmitted to a home computer for diagnosis of the patient's cardiovascular conditions. This continuous monitoring system can provide unique and useful information for preventive diagnosis in which long-term trends and signal patterns are more important. The ring sensor is completely wireless and miniaturized so that the patient can wear the device comfortably twenty-four hours a day. The objective of this paper is to provide detailed descriptions of the hardware and software of the ring sensor. Also, the effects of motion artifact and ambient light will be investigated.

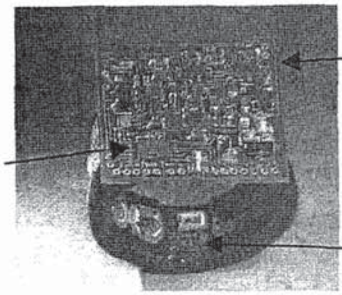

Figure 1 : The photograph of the finger ring sensor. The size of the circuit board on top of the ring is 0.8 by 0.8 inch.

2. Method

A finger ring is a unique form of wearable sensors and, probably, the only thing that the majority of people will accept to wear at all times. To monitor a patient twenty-four hours a day continually, a miniaturized sensor in a ring is a rational design choice. Other personal ornaments and portable instruments, such as ear rings and wrist watches, are not continually worn in daily living. When taking a shower, for example, people remove wrist watches. Bathrooms, however, are one of the most dangerous places in the home. More than 10,000 people, mostly hypertensives and the elderly, die in bathrooms every year. Miniature ring sensors provide a promising approach to guarantee the monitoring of a patient at all times.

LEDs with two different wavelengths, red and near infra-red, as well as a photodiode are imbedded in the ring facing inwardly. The red and infra-red LEDs are alternately turned on and the output from the photodiode is amplified and switched to a sample-and-hold filtering circuit to generate a piecewise constant wave for each wavelength of light. This alternative and sample-and-hold sequence is repeated at the frequency of 1000 Hz to eliminate light interference even in a quickly changing background of room lights. The resultant waves are filtered and conditioned as photoplethysmograms. An 8-bit A/D converter samples each photoplethysmogram at the frequency of 30 Hz and the digital signals are transmitted by a RF wave through the standard RS-232 protocol. The whole process is scheduled and controlled by a single microprocessor on the ring.

Transmitted photoplethysmograms are received and analyzed by a home computer. The technology of pulse oximetry [4] is implemented on the computer for continuously monitoring the patient's pulses and blood oxygen saturation. Although the signal is already filtered and refined by the analog signal conditioner in the ring sensor, it still contains the high frequency noise due to an ambient light source and motion artifact. For example, Figure 2 (a) shows a steady photoplethysmogram without having any artifact, whereas Figures 2 (b) and (c) show the signal contaminated with the influence of ambient light and motion artifact respectively. It is clearly seen that the contaminated signal carries high frequency noise even though it already passed through a hardware lowpass filter. When the host computer detects these high-frequency noise, the computer does not display the wave forms on the screen nor uses them for pulse oximetry.

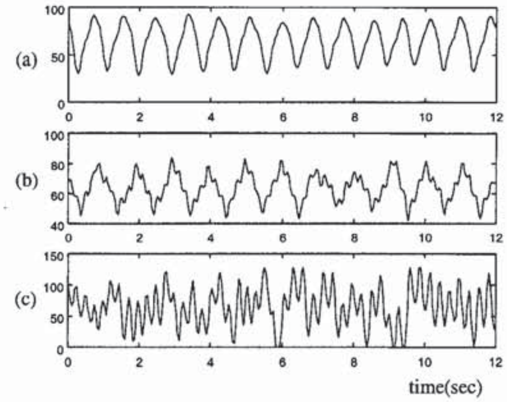

Figure 2 : Various signals detected by the ring sensor

3. Hardware Description

A block diagram of the ring sensor is shown in Figure 3. All of these components are contained in a small circuit board of 0.8 by 0.8 inch, as shown in Figure 1. Each of the blocks in the diagram is explained in detail as follows.

3.1. LEDs and Photodiode

One red LED and two infra-red LEDs are used as the light sources. The peak wavelength of the red LED is 660 nm, and that of the infra-red LEDs is 940 nm. The photodiode has the peak wavelength of 940 nm and spectral sensitivity ranges from 500 nm to 1000 nm, which meets our needs. The voltage drop of the red LED is 1.6 V and that of the infra-red LEDs is 1.2 V, and two infra-red LEDs are connected in serial. We used LEDs in a die form and the diameter is less than 0.1mm.

3.2. First-Stage Amplifier.

The first stage amplifier must be fast enough to keep in pace with the flickering speed of the LEDs, which means that it must have a high slew rate. On the other hand, it is not desirable if this amplifier consumes a lot of power. We chose OPA336 surface mount style amplifier from Burr-Brown. This amplifier has 0.03 V/μs of slew rate which is quite high for a 20 μA low power amplifier. Furthermore, this amplifier is designed to be used as a pre-amp for photodiode, which also satisfies our need.

3.3. Sample-and-Hold Circuit

Since one photodiode is shared by two channels of signal conditioner, the sample and hold circuit is necessary to hold the right signal for a brief moment. The two LEDs are alternatively lit and the two bilateral switches are also in synchronization with the LEDs. When the red LED is on, the bilateral switch (MC14066B from Motorola) of the first channel is turned on to make the signal flow into the first channel. When the infra-red LED is on, the switch on the second channel is turned on and the signal is held by the sample-and-hold circuit. With these sampling-and-hold channels, the single photodiode can generate two wave forms from the different LEDs at the same time. The sample-and-hold circuit comes with a 1000 pF capacitor which is enough

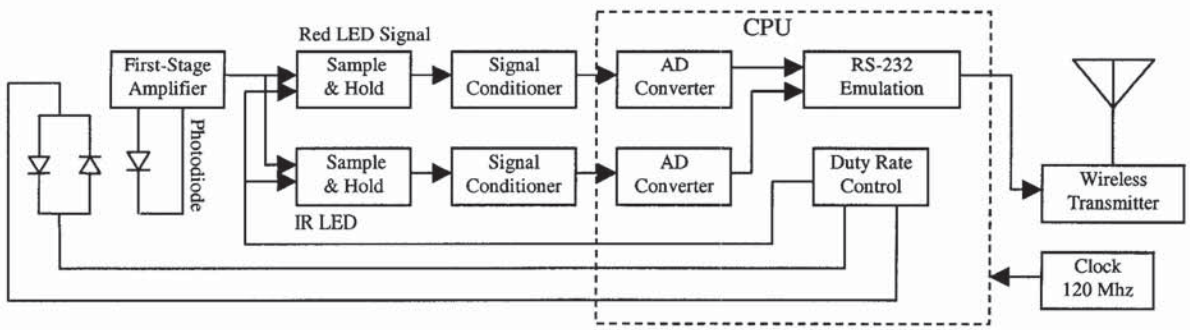

Figure 3: Block diagram of the ring sensor

to hold the signal for a while. To reduce the circuit size to that of a real ring, die-form chips are used and the connections were done by wire bonding machine that uses extremely thin gold wire.

3.4. Signal Conditioner

The signal conditioning part is composed of filters and amplifiers. Since the signal from the first stage amplifier is weak in a milli-volt range, it must be amplified by the order of 1000 times. We used a MAX407 operational amplifier from Maxim for the signal conditioner stage. One of the major reason for choosing this amplifier is that it consumes extremely low power which is around 1.2 μA per amplifier. In this stage, the slew rate is not an important factor since the frequency of interest at this stage is less than 10 Hz. This amplifier is also used in a lowpass filter circuit. The lowpass filter cuts off most of the frequency components higher than 20 Hz. Also there is a simple highpass filter circuit composed of a resistor and a capacitor that removes DC components. We used die-form integrated chips and wire-bonding-style resisters of which size is on the order of 20 by 40 mil.

3.4. CPU

The CPU on the board controls all the operations of the ring, from scheduling LEDs to digitally converting acquired analog signals to formatting the signals in a RS-232 form for transmission. Since the CPU is one of the major components of power consumption, it has to be chosen carefully. For the purpose, we chose a PIC16C711 from Microchip. This CPU has two channels of embedded A/D converter, 8 channels of digital I/O line. It has 1 KB of EPROM which is enough for the code that satisfies our task. An advantage of this chip is that it consumes very low power (usually less than 40 μA with 32 kHz clock speed.) in the normal operation mode and almost no power in the sleep mode. This chip even comes with built-in RS-232 signal generation function. However, we didn't use that function, since a much higher clock speed is necessary to obtain a satisfactory baud rate if we are to use this built-in RS-232 generator which will result in more power consumption.

3.5. RF Transmitter

The piecewise constant waves generated at the LED circuit are converted to digital signals by an 8-bit A/D converter and transmitted through a RF wave by the microprocessor. The transmitter is simply a ON/OFF transmitter. In other words, it transmits signal when the input is high, and does not transmit anything when the input is low, hence, the power is consumed only when the input is high. We can save the power by reducing the width of the '1' bit, which will happen when we use a higher baud rate. Currently we are using 600 and 1200 bps.

4. Software Description

4.1. Software for the Microprocessor on Ring Side

The assembly program was loaded in the microprocessor on the ring sensor. The first process of the code is the initialization of the CPU. Then it triggers the A/D conversion of a channel. During the A/D conversion delay, it retrieves a number from another A/D channel. Then it transmits the number in RS-232 format. To match the timing of a certain baud rate, we counted the number of the instructions executed to send one bit, and calculated the time for one bit transmission. Each 8 bit number is sent with a start bit and a stop bit which complete the RS-232 protocol. This process is done in both channels in turns.

4.2. Software for the Host Computer

A RF receiver receives transmitted signals in the RS-232 form and transmits the data to the home PC thought a serial port. The software on the host computer is run under the Windows 95 or Windows NT environment. It is programmed using Microsoft Visual C++ 5.0, and uses the standard serial communication programming technique. It is natural that the program has to be in the standard Win32 program format, and this format has to start with initialization of the windows and the variables.

Apart from the standard windows programming routines, most of the program is dedicated to detecting the faulty signal and removing those noise signal from the clean heart beat signal. The multi-threading routines check the serial port continuously to find out if any data have arrived. As soon as some data arrive at the serial port, the program counts the number of red LED signal and the number of infra-red signal. If the signal transmission was done correctly, the two numbers must be almost exactly the same. If this is not the case, this means that there was some problem with signal transmission. In this case, the program considers the received signal as noise and ignore them. If the number of red LED signal and that of infra-red are more or less the same, then the program checks the frequency component of the received data. If the data includes any strange high frequency components such as that of Figure 4 and Figure 5, the program thinks that these data were contaminated by motion artifact or ambient light influence, and discard them. If the received signal passes through these filtering processes, the program accepts the data as valid ones and display them on the screen. The program also measures the peak-to-peak distance at this stage and calculates the pulse rate. The same process is done continuously whenever any data is detected available at the serial port.

5. Validation of the Device

To establish the validity of this instrumentation system, two kinds of experiments were conducted. The first experiment was designed to test how well this system detects motion artifact. After the signal from the ring sensor becomes stabilized, the wearer shakes his hand so that the signal becomes distorted due to the motion artifact. Figure 4-(a) shows the actual signal received at the host computer and the Figure 4-(b) shows the data displayed on the screen. As the signal begins to be contaminated by the motion artifact from t=12 (sec), the software on the host computer detected a high frequency noise as well as a saturation of the signal to conclude that this is not the valid signal, and ignored the received signal and displayed just a flat line. Figure 5 shows the next experiment to test the detection of the noise from the ambient light source. At around t=11 (sec), the person took off the ring and put it on the table. Naturally the signal after this point is not a valid signal and only noise from ambient light would be acquired. Figure 5-(a) shows the actual data received by the host computer. The software detected the high frequency noise but no saturation. Therefore it concluded that this signal is not the valid signal. Figure 5-(b) shows the actual display on the screen as a flat line after the person took off the ring, which indicates that the system was not confused by the ambient light source and clearly discriminated the noise from the right signal.

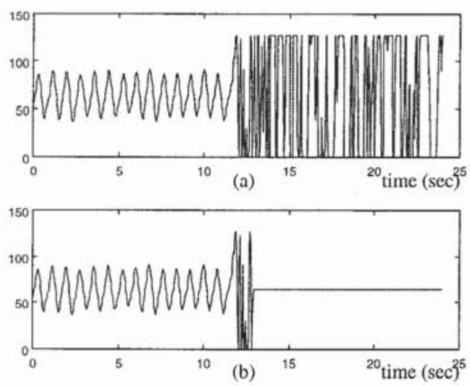

Figure 4 : Signal contaminated with motion artifact (a) Actual signal received by the host computer from the ring sensor. The person began to shake his hand from t=12 (sec). (b) Signal displayed on the screen. The host computer detected the motion artifact and ignored the signal, putting only a flat line after t=12 (sec).

6. Conclusions

In this paper, a twenty-four hour patient monitoring system using the ring sensor has been presented. The ring sensor is equipped with optoelectrical components for monitoring a patient's arterial blood flow in a finger base. A wireless transmitter on the ring sensor sends measured signals to a home computer through multiple receivers for diagnosis and abnormality detection. The host computer analyses the received data and discriminate the valid signal from the noise from motion artifact or ambient light source. The ring sensor and the monitoring system have the following distinctive features:

- Measurement of photoplethysmograms and oxygen saturation for diagnosis of the patient's cardiovascular conditions.
- Continuous monitoring to provide unique and richer physiological data.
- Discrimination of valid heart beat signal from the noise generated by other sources.

The hardware and the software of the system were described in detail, and the methods of avoiding a faulty heart beat detection due to the interference of the motion artifact and the ambient light were suggested and verified. The experimental results show that the invalid noise can be discriminated from the valid signal effectively by detecting the high frequency component and the saturation of the signal.

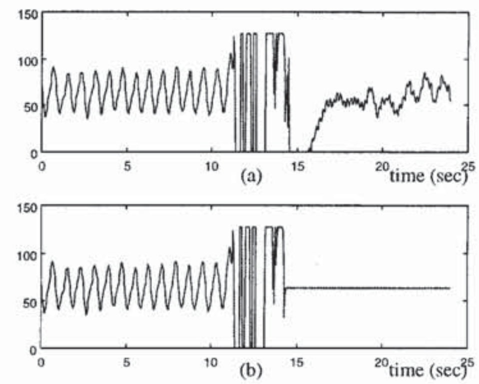

Figure 5 : Signal contaminated with ambient light influence. (a) Actual signal received by the host computer. The person took off the ring sensor at t=11 (sec). After this point the signal is purely the noise from ambient light. (b) The host computer detected the high frequency noise from ambient light, and displayed just a flat line after the detection.

Acknowledgement

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