Artifact-Resistant, Power-Efficient Design of Finger-Ring Plethysmographic Sensors
Part I : Design and Analysis

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Abstract-- A miniaturized, telemetric, photoplethysmograph sensor for long-term, continuous monitoring is presented in this paper. The sensor, called a "ring sensor", is attached to a finger base for monitoring beat-to-beat pulsation, and the data is sent to a host computer via a RF transmitter. Two major design issues are addressed: one is to minimize motion artifact and the other is to minimize the consumption of battery power. An efficient double ring design is developed to lower the influence of external force, acceleration, and ambient light, and to hold the sensor gently and securely on the skin, so that the circulation at the finger may not be obstructed. In this paper, the basic concept of mechanical and electrical design is provided. Total power consumption is analyzed in relation to characteristics of individual components, sampling rate, and CPU clock speed. Optimal operating conditions are obtained for minimizing the power budget.

Index Terms— ring sensor, ambulatory monitoring, plethysmograph, motion artifact, power consumption, telemetry, wearable sensor, beat-to-beat pulsation.

I. INTRODUCTION

As the population of aged people increases, vital sign monitoring is increasingly important for securing their independent lives. On-line, continuous monitoring allows us to detect emergencies and abrupt changes in the patient conditions. Especially for cardiac patients, on-line, long-term monitoring plays a pivotal role. It provides critical information for long-term assessment and preventive diagnosis for which long-term trends and signal patterns are of special importance. Such trends and patterns can hardly be identified by traditional examinations. Those cardiac problems that occur frequently during normal daily activities may disappear the moment the patient is hospitalized, causing diagnostic difficulties and consequently possible therapeutic errors. Continuous and ambulatory monitoring systems such as ambulatory ECG are therefore needed to detect the trait.

The ambulatory ECG (Holter) device, one of the most widely accepted ambulatory monitoring systems, was developed and extensively studied by N.J. Holter [1]. The ambulatory ECG, however, is not applicable to long-term monitoring for a period of several weeks or months. The machine is bulky, heavy, and uncomfortable to wear due to cumbersome wires and patches. Recently, a variety of vital sign sensors have been developed that are compact and easy to wear. Wristwatch-type pulse oximetry and blood pressure sensors have been developed and commercialized by several companies including Casio (BP-100 and JP200W-1V) and Omron (HEM-608 and HEM-609). These devices, although much easier to wear, have not yet been used clinically. Many technical issues still need to be solved for clinical use.

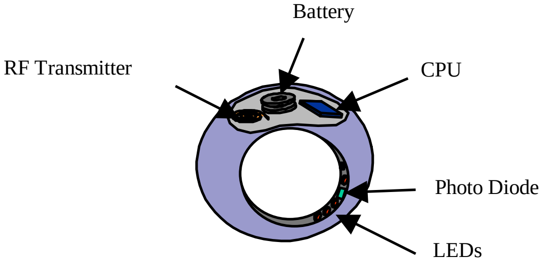

Figure 1 : Conceptual diagram of the ring sensor

In general, long-term, ambulatory monitoring systems have not yet reached a technical level that is widely accepted by both clinicians and patients. Such long-term, ambulatory devices must be compact, lightweight, and comfortable to wear at all times. They must be designed for low power consumption for long term use. Furthermore, they must be able to detect signals reliably and stably in the face of motion artifact and various disturbances. Unlike traditional monitoring systems, these devices are used under no supervision of clinicians. Data is collected from daily lives of patients in an unstructured environment.

The goal of this paper is to develop technology for reducing motion artifact and obtaining reliable measurements of vital signs for long-term use. A miniaturized photoplethysmograph (PPG) device in a ring configuration will be designed. It will be shown that the device meets diverse and conflicting requirements, including compactness, motion artifact reduction, and low battery power consumption.

II. THE RING SENSOR

A. Basic Construction

The ring sensor is a miniaturized, telemetric, monitoring device worn by a patient as a finger ring. This device optically captures the pulsation and oxygen saturation of the arterial blood flow, and transmits the signals to a host computer via a RF transmitter. Figure 1 shows a conceptual diagram of the ring sensor [2][3]. The ring sensor consists of optoelectronic components, a CPU, a RF transmitter, a battery, and a ring chassis. The optoelectronic components, i.e. micro photodiodes and LEDs, detect the blood volume waveforms and oxygen saturation level at the patient's digital artery. The CPU controls the LED lighting sequence as well as the data acquisition and transmission process. These signals are locally processed by the on-board CPU and transmitted to a host

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computer for diagnosis of the patient's cardiovascular conditions.

B. *Technical Issues*

The ring sensor, however, is inevitably susceptive to a variety of disturbances such as a patient's motion and ambient lighting. When the patient moves, the inertia force created at his/her finger causes the ring to move relative to the skin surface, and as a result, measurement may be distorted or even ruined completely. When the ring touches an environment surface, the contact force may cause a distortion of the measurement due to the relative displacement of the sensor to the finger. In addition, ambient lighting is another major source of artifact for optical measurement. These kinds of disturbances degrade the quality of measurement and would make the ring sensor an unreliable device. Therefore, the ring sensor must be designed in such a way that the influence of disturbances can be minimized.

In addition, the whole electronic circuit must be designed for minimum power consumption in order to operate it for a long time without changing or recharging the battery. Among others, LED is one of the most power-consuming parts involved in the ring sensor. Therefore, the intensity of the LEDs must be lowered along with the reduction of duty cycle. This, however, incurs a poor signal-to-noise ratio problem. The signals obtained with dark LEDs are weak and must therefore be amplified many thousand times. As a result, it becomes susceptive to any disturbances.

III. ARTIFACT-RESISTANT MECHANICAL DESIGN

A. *Isolating Ring Architecture*

Figure 2-(a) shows the cross-sectional view of the original ring sensor where the optoelectronic sensor unit, i.e. the LEDs and photodiodes, is attached directly to the body of the ring. The problems with this design are:

- When the ring touches the environment surface, the ring is pushed to one side, creating an air gap between the sensor unit and the skin, or increasing the pressure with which the sensor unit is attached. This incurs significant fluctuation in the sensor reading.
- The body of the ring sensor, including the battery and circuitry, tends to be heavy. A small acceleration of the finger and even the gravity of the ring itself may cause a displacement relative to the skin surface. Securing the ring body requires a large force applied to the finger skin.
- It is difficult to shield the sensor unit from the ambient lighting.

To resolve these problems of the original ring design, a new design is presented in this section. The main idea of new this design, called a "isolating ring configuration", is to separate the sensor unit from the rest of the ring body that is much heavier than the optical sensor unit alone. The separation is achieved by having two rings that are mechanically decoupled to each other. The inner ring holds sensor unit alone, while the outer ring contains the CPU, signal processing unit, battery, and RF transmitter. Only a thin, flexible cable connects the two rings. This decoupled design has the following advantages.

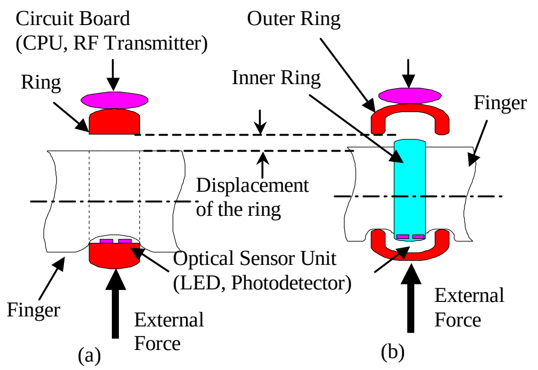


Figure 2 : Dislocation of ring sensors due to external load
(a) Traditional single body design under external force
(b) New isolating ring sensor under external force

Alleviating the influence of external forces applied to the ring

Forces due to mechanical contacts are born by the outer ring, and are not directly transmitted to the sensor unit on the inner ring. As shown in Figure 2-(b), the load of the external force is bypassed to the finger bone and is supported by the two feet of the bridge-like outer ring.

Alleviating the effect of acceleration on the sensor

The inertia of the sensor unit is very small since it contains only a few LEDs and photodiodes. Due to the small inertia of the inner ring, the inertia force acting on the sensor unit is negligibly small. In consequence, the position of the optical sensor does not change significantly although the finger is accelerated.

Reducing the skin pressure

The outer ring doesn't have to be secured tightly, while the inner ring doesn't need a large pressure to secure the body, since it is light. Therefore, the possibility of necrosis caused by local ischemia and occlusion is lowered. This solves a critical problem for wearable sensors and long-term monitoring systems such as the ring sensor.

Reducing the influence of the ambient lighting

The outer ring shields the sensor unit and thereby reduces optical disturbances from the ambient lighting. The isolating ring structure provides the sensor unit with an optical shield.

Thus the isolation ring structure resolves those critical problems of the original single-body ring sensor.

IV. POWER SAVING ELECTRONICS DESIGN

A. *Power Budget*

Among many components involved in the ring sensor, the LEDs and the RF transmitter consume over 70% of the total power, hence a saving in these components makes a significant contribution to the overall power saving. The objectives of this section are to provide a detailed power budget of the ring sensor, and to present an approach to minimize power consumption at the LEDs and the RF transmitter while satisfying specifications of the ring sensor. The power budget may differ depending on specific algorithms and control schemes for operating the LEDs and RF transmitter. In the following, a power budget will be obtained for a specific control algorithm that is simple and feasible to implement on a miniaturized ring sensor. For different algorithms, a power budget can be obtained without difficulty in the same way as the following formulation.

LED

LEDs consume a large amount of power when emitting light continuously. Therefore they must be switched on only for a short interval when light must be emitted. Namely, the LEDs must be on only when the photodiode is detecting the reflected light for measuring the pulsation. Synchronizing the sampling of the photodetector with the LED switching reduces the duty ratio of the LEDs, and thereby reduces the power consumption. In the prototype system, this coordination is performed by the microprocessor. First the LEDs are turned on, second the photo detector signal is sampled at the next CPU cycle, and the LEDs are switched off at the third CPU cycle. This sequence control is performed for both red and infrared LEDs. As the CPU clock cycle increases, the duty ratio of the LEDs decreases, hence the power consumption decreases. However, the CPU consumes more power as the clock frequency increases. Therefore, a trade-off must be made between the CPU power and the LED power in order to minimize the overall power consumption.

Key parameters associated with the LEDs' power consumption are:

q : internal clock frequency of the microprocessor (Hz)
f : sample-and-hold frequency (Hz)
r : duty ratio of LEDs
C_r : total power consumption of the red LED circuit per second
C_i : total power consumption of the infrared LED circuit per second

In the above lighting sequence, both red and infrared LEDs are turned on for three internal CPU clock cycles, that is, $3 / q$ seconds. Therefore the duty ratio of LEDs is $r = 3f / q$. The average power consumption of the LEDs is given by

$$P_l(q) = r(C_r + C_i) = \frac{3f(C_r + C_i)}{q} \tag{1}$$

Microprocessor

In general, power consumption of a microprocessor increases with clock speed. In the prototype ring sensor, a linear relationship exists between power consumption and clock speed q:

$$P_m(q) = aq + b \tag{2}$$

where the coefficients a and b can empirically be determined.

RF Transmitter

The sampled analog signals are converted to digital signals by an A/D converter and transmitted through the RF transmitter controlled by the same microprocessor. The transmission protocol is the standard RS-232 using simple on-off keying. The most power-consuming part of the digital RF transmitter is an oscillatory circuit involving a CMOS power transistor, which consumes a significant amount of power only when the output is high, i.e. 1-bit. In other words, the power consumption is virtually zero, when the output is low, i.e. 0-bit. Therefore, power can be saved by reducing the pulse width of each 1-bit. In the standard RS-232 protocol, the width can be reduced simply by increasing the baud rate. As the baud rate increases, transmission is completed in a shorter period of time, leaving a longer time for the transmitter to be in an idle state with no power consumption. However, a higher baud rate of the transmitter requires a higher clock frequency for the microprocessor, which results in larger power consumption. Similar to the previous case, a trade-off must be made between the CPU power and the transmitter power. We now formulate the power budget of the transmission circuit and optimize the power consumption in terms of the clock frequency.

Key parameters associated with RF transmission are:

d : baud rate of transmission (bps)
n : number of sample points to be transmitted per second (Hz)
m : average number of high bits to be transmitted per second (bps)
C_t : total power consumption of the transmission circuit per second

Transmission of one bit needs at least 6 CPU instructions, including branching, port setting, carrier setting, and bit-shifting instructions. Therefore it takes 6 internal CPU clock cycles. Namely, the fastest baud rate for a given clock frequency is $d = q / 6$. In the prototype ring sensor, the resolution of the A/D converter is 8 bits; hence one sample point is one byte of data. Including start bit and stop bit, the standard RS-232 protocol needs five high bits to transmit on average per sample point (one byte) resulting in $m = 5n$. Therefore, the average duty ratio of the RF transmitter transmitting a high bit is $m / d = 30n / q$. The average power consumption due to RF transmission is therefore given by

$$P_t(q) = \frac{30nC_t}{q} \tag{3}$$

The total average power consumption of the LEDs, RF transmitter, and microprocessor is,

$$\begin{aligned} P_T(q) &= P_l(q) + P_t(q) + P_m(q) \\ &= \frac{3f(C_r + C_i)}{q} + \frac{30nC_t}{q} + aq + b \end{aligned} \tag{4}$$

The optimal internal clock frequency q^* can be obtained by differentiating the above equation and equating it to zero:

$$q^* = \sqrt{\frac{3f(C_r + C_i) + 30nC_t}{a}} \tag{6}$$

B. *The Power-Optimal Clock Frequency*

Based on the power budget model obtained in the previous section and power consumption characteristics of each part selected, the optimal clock frequency for minimizing the overall power consumption will be obtained in this section. The power consumption parameters associated with the red and infrared LEDs are:

$C_r=2.3\times10^{-3}$ (Ampere), $C_i=0.5\times10^{-3}$(Ampere)

Note that the unit of these parameters is the Ampere rather than the Watt to be consistent with the battery capacity unit of Ampere-hour. The CPU power consumption model, eq.(2), was identified through experiment. The coefficients involved in the model, a and b, are given in Amperes by

$a=1.993\times10^{-9}$ (Ampere/Hz), $b=6.553\times10^{-6}$ (Ampere)

For the prototype ring sensor, the required sample-and-hold frequency is $f = 1000$ Hz. The number of sample points that the RF transmitter must transmit per unit time is $n = 60$. The current consumption of the transmitter circuit was identified as:

$$C_t=4.0\times10^{-3} \text{ (Ampere)}$$

Substituting these parameters into eq.(6) yields the optimal clock frequency for the CPU:

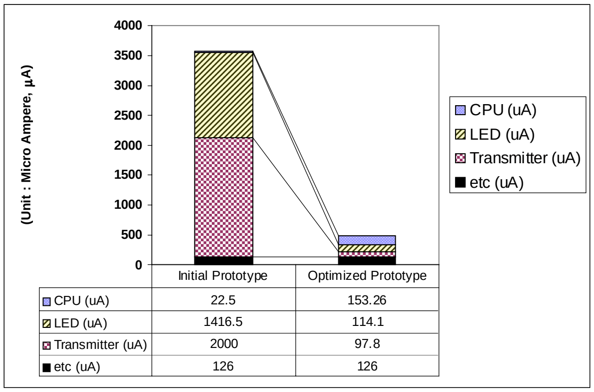
$$q^* = 73.61 \text{ kHz}$$

And the minimized current consumption is given by

$$P_T(q^*) = 0.365 \text{ mA}$$

The other electronic components of the ring sensor include multiple op-amps, switches, sample-and-hold, and filters. The total current consumption of these components was found to be *0.126 mA*. Therefore, the optimal total current consumption of the ring sensor is *0.491 mA*, or *1.473 mW* with *3V* batteries. Figure 3 shows the comparison of the power optimal design with the initial non-optimal design. The power optimal design has reduced the power consumption to *1/7* of the original design, where r = 0.5, d = 600 bps, and q= 8,000 Hz. In particular, the power consumption of the RF transmitter has reduced to *1/20*, while that of LEDs has reduced to *1/12*. Based on these data, the battery life, i.e. the length of continuous measurement without changing the batteries, can be obtained. In the prototype ring sensor, two separate batteries are used. The RF transmitter consumes 0.098 mA in the optimal design. Therefore the lithium battery of *75 mAh* capacity can last for 31.9 days. On the other hand, the CPU-LED circuit consumes 0.393 mA, and can run continuously for 23.3 days with the lithium battery of *220 mAh*. If the continuous measurement is not required, but some intermittent measurement suffices, the battery life can be extended to several months to a year.

V. CONCLUSION



	Initial Prototype	Optimized Prototype
CPU (uA)	22.5	153.26
LED (uA)	1416.5	114.1
Transmitter (uA)	2000	97.8
etc (uA)	126	126

Figure 3 : Comparison of Power Budget

An artifact-resistive and power-efficient design of ring sensors has been presented. The main results of this paper are:

- The isolating ring design developed in this paper decouples the optical sensor unit from other components, and allows the sensor unit to be shielded from external static loads and the ambient lighting. The new ring design also attenuates the influence of finger acceleration, since the heavy components are mechanically decoupled from the sensor unit. This allowed us to hold the sensor unit with a small skin pressure, so that the circulation at the finger may not be obstructed.
- The power consumed in the ring sensor has been analyzed in relation to the characteristics of individual parts, sampling rate, transmission rate, LED lighting schedule, and CPU internal clock frequencies. Based on this power budget analysis, low-power components have been selected, power-efficient LED lighting and RF transmission methods have been developed, and the optimal CPU clock frequency has been obtained. With small battery cells, the ring sensor can continuously detect and transmit plethysmograph signals for 23.3 days, while the battery life can be extended to several months with an intermittent measurement schedule.

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Track: 22 Bioinstrumentation and Biosensors

Short Paper Available

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