

A Twenty-Four Hour Tele-Nursing System Using a Ring Sensor

Boo-Ho Yang, Sokwoo Rhee, and Haruhiko H. Asada
d'Arbeloff Laboratory for Information Systems and Technology
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139, U.S.A.

Abstract

The objective of this paper is to present the recent development of the ring sensor to monitor a patient 24 hours a day for a tele-nursing system. The ring sensor is worn by the patient at all times, hence the health status is monitored 24 hours a day. The sensors packed into the ring include LEDs with different wavelengths, and technologies of photoplethysmography [1-2] and pulse oximetry [3-4] are implemented on the ring. The sensor data are transmitted to a computer through the digital wireless communication link and the patient status is analyzed continually and remotely. Any trait of abnormal health status and possible accidents is detected by analyzing the sensor data. A combination of a global receiver and multiple local ones are used to estimate the patient's location and activity, e.g. taking a shower in the bathroom, using a toilet, sleeping in a bed, and ascending/descending the stairs. Both the physiological data and the position information can be used to make an accurate decision as to whether a warning signal must be sent to a medical professional caring the patient. An issue of power reduction for miniaturization of the ring sensor is also addressed and the power saving algorithm will be developed. This monitoring system is particularly useful for tele-nursing systems for home-based elderly care.

1. Introduction

Close and continuous monitoring is a critical technology for tele-nursing systems. For example, since the population of aged people living alone is constantly increasing, health monitoring for these people at home is highly demanded. Also, effective technologies for remotely and continuously monitoring the patient status and detecting any trait of abnormal conditions and potential risks after being discharged from the hospital are badly needed. A couple of compact, continuous monitoring devices have been developed [5-6] for the

purpose of elder care. However, these devices have not

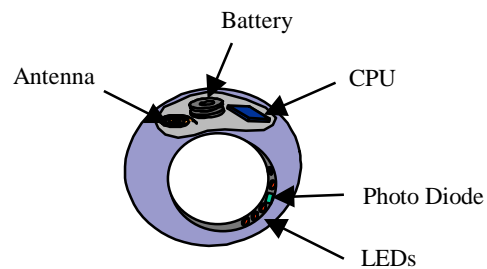


Figure 1: Conceptual diagram of the ring sensor

been widely accepted since the lack of functionality for measurement and comfort for wearers.

To answer these demands, we have developed a compact, wearable monitoring system in a ring configuration that can be comfortably worn by the patient twenty-four hours a day and that transmits data to a computer through a wireless communication. Figure 1 shows a conceptual diagram of the ring sensor. The ring sensor is equipped with optoelectric components that allow to monitor patient's arterial blood volume waveforms and blood oxygen saturation non-invasively and continuously. These signals are transmitted to a home computer for diagnosis of the patient's cardiovascular conditions. This continuous monitoring can also 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.

A key issue for developing such a compact, wearable sensor is how to reduce its power consumption while operating continuously. Since the determinant factor of the dimension and weight of the ring sensor is those of a battery cell to be used, reduction of the power consumption is extremely important for miniaturization of

the sensor. The objective of this paper is to present the detailed descriptions of the ring sensor as well as an efficient technique to minimize the power consumption

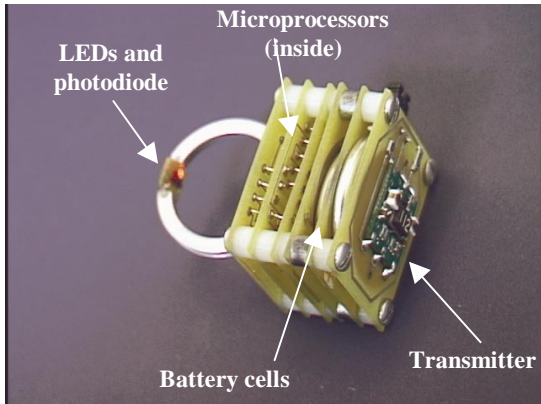


Figure 2: A prototype of the ring sensor

while satisfying the specifications of the ring sensor. In section 2, the components, specifications and features of the ring sensor are described in detail. Section 3 provides the power budget of the ring sensor and an approach to minimize the power consumption of the ring sensor while maintaining the specifications of the sensor so that the ring sensor can operate for a long period of time without replacing the battery cell. The conclusions are presented in Section 4.

2. Ring Sensor for Patient Monitoring

A finger ring is probably only the 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 elder, die in bathrooms every year. Finger ring miniature sensors provide a promising approach to guarantee the monitoring of a patient at all times. Also, a ring configuration provides the anatomical advantage of having transparent skin and tissue at the finger compared with other part of the body so that it is feasible to monitor arterial blood flow at the finger base using a optoelectric sensor. Subsequently, a variety of simple cardiac and circulatory disorders may be detected by monitoring arterial blood flow at the finger base.

To demonstrate the concept, we developed a prototype ring sensor with a wireless transmitter. Figures 2 and 3 show a photograph and the block diagram of the prototype ring sensor, respectively. As shown in the figures, LEDs with two different wavelengths, red and near infrared, as well as a photodiode are imbedded in the ring facing inwards. The red and infrared LEDs are alternately turned on and output from the photodiode is amplified and switched to a sample-and-hold filter to generate a piecewise constant wave for each wavelength of light. Another piecewise constant wave is generated from output due to ambient lights and subtracted from the above waves to eliminate ambient light artifact. The above alternation 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

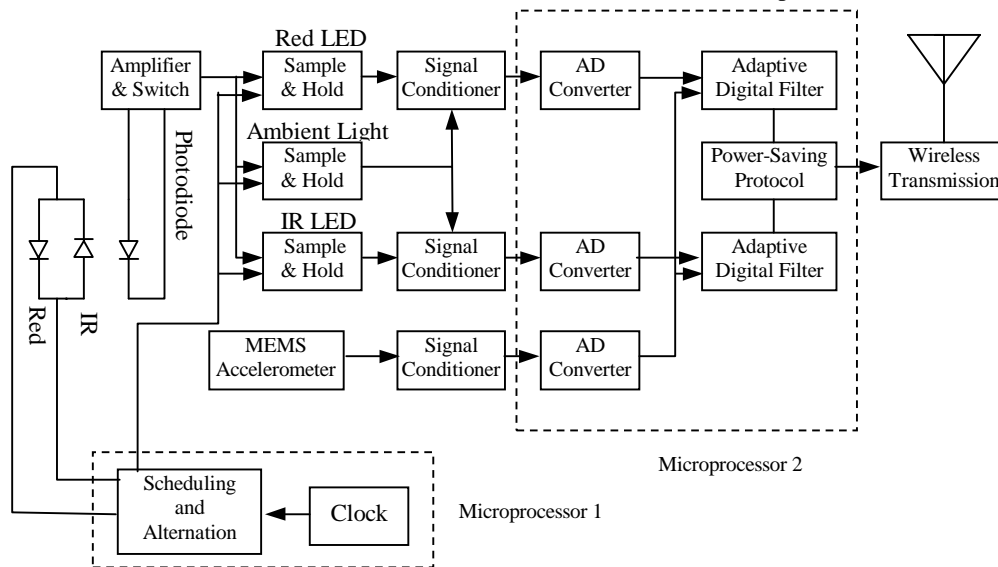


Figure 3: Block diagram of prototype ring sensor

scheduled and controlled by multiple microprocessors.

Using the prototype ring sensor, a twenty-four hour patient monitoring system has been developed. In the patient monitoring system, receivers are placed at appropriate places in a home and are connected with a home computer through serial cables. The home computer analyzes the transmitted data and sends a warning signal to a telenursing center through a telecommunication channel such as internet if any abnormality is detected. Figure 4 shows all the components of the monitoring system.

The ring sensor and the twenty-four hour patient monitoring system have the following distinctive features:

Photoplethysmography and Pulse Oximetry for Diagnosis

The ring sensor measures and transmits photoplethysmographic signals to the home computer in real time. The photoplethysmograms provide a rich variety of diagnostic information, from which a class of cardiac and circulatory disorders can be detected. For example, a recent investigation has revealed that the likelihood of heart attack can be predicted by examining the rhythm of a plethysmogram over a long period of time. Also, peaks of the acceleration plethysmogram, that is, the curve obtained by twice differentiating the original plethysmogram, provide important information for arteriosclerosis diagnosis. Pulse oximetry was also implemented in the ring sensor using two wavelengths of light, as shown above. A patient's saturated oxygen level is known to provide one of the most fundamental physiological variables needed for diagnosis of cardiovascular disorder such as congestive heart failure.

Continuous Monitoring

Twenty-four hour continuous monitoring can be performed for an extended period of time, i.e. many months or years. This would provide unique physiological data and allow new types of healthcare services, which would be difficult to provide in traditional hospital facilities. Traditional medical exams conducted at hospitals are inevitably snap-shot data or short-term data taken under special conditions, while ring sensors would provide continuous, long-term data of vital signs. Diagnosis can be made based on vast amount of data points, trends, and signal patterns as well as transitory and fugitive symptoms. By exploiting this continuous monitoring feature, we can develop an innovative health monitoring system that not only diagnoses the patient's health status but also predicts the likelihood of emergency and serious conditions.

Patient's Location Estimation

The location of the ring wearer can be roughly estimated by the ring sensor. Since the power of the radio

transmitter is very small, the signal reaches only in a limited range. Therefore, the detectable signal range is localized and the possible wearer's position is confined within a local range. In the monitoring system, we use two types of the receivers: a global receiver and local receivers. The global receiver has a broader range of reception and covers almost the entire house. A local receiver has a narrower range and located in multiple places in the house. The objective of using many local receivers is twofold:

- To cover the entire house: No matter where the wearer moves within the house, the monitoring signal must be received.
- To locate the ring wearer: Examining which local receiver within the house receives the incoming signal, one can locate the ring wearer.

The location of the patient provides useful information, which would supplement physiological measurements. Combining the patient's location information with physiological data, the patient's conditions can be better understood. For detecting emergency situations, for example, the patient's location within the home is critically important. If the ring wearer stays in a bathroom for more than an hour, or stays in a staircase area for a half hour, the physiological variables must be scrutinized to detect a possible emergency case. Furthermore, the patient's location information can be used for interpreting the physiological variables, since the type of the patient's activity is related to a particular location within the home, i.e. shower room for taking a shower, bed room for rest, staircase for leg motion. Correlating the location and activity information with vital signs would provide much richer information about the patient's health status than simply observing the vital signs alone.

3. Power Saving Algorithm for the Ring Sensor

One of the main issues for developing the ring sensor is how to reduce its power consumption of the electrical components involved in the ring sensor. Since the determinant factor of the dimension and weight of the ring sensor is those of a battery cell to be used, reduction of the power consumption is extremely important for miniaturization of the sensor. Among many components involved in the ring sensor, LEDs and a RF transmitter consume over 70 % of the total power, hence saving in these components will make a significant contribution to the miniaturization of the ring sensor. The objectives of this section are to provide a detailed power budget of the ring sensor and to present an approach to minimize the power consumption of the LEDs and the RF transmitter while satisfying the specifications of the ring sensor. Since the microprocessors to control the LEDs and the RF

transmission circuits operate independently, the power optimization approaches of these components are derived and presented separately as follows.

LEDs

In the ring sensor, the two groups of LEDs, near infrared and red, are emitting light alternately, and the emission process is controlled and scheduled by a microprocessor. Considering the efficiency of signal detection and its power consumption, the light from the LEDs must be emitted intermittently. It is obvious that the power consumption of these LEDs can be significantly reduced if the duty ratio of the LEDs' emission is decreased. Since the duty ratio is solely depending on the internal clock speed of the microprocessor, the microprocessor must be driven at a faster clock to decrease the duty ratio. However, it is also known that the power consumption of the microprocessor is linearly increasing with the clock speed. Hence, it is inevitable to find the optimal clock frequency to minimize the total power consumption.

Let us define the key parameters of the power budget as follows:

- q_l : internal clock frequency of the microprocessor (Hz)
- f : sampling and holding frequency of the LEDs (Hz)
- r : duty ratio of the LEDs
- C_r : total current consumption of red LEDs (A)
- C_i : total current consumption of infrared LEDs (A)

Note that the internal clock of the microprocessor on the ring sensor is created by an external clock and the frequency of the external clock must be to $4q_l$. Also, since each LED must be on at least for three internal CPU clock cycles for sampling and holding, as shown in Figure 5, the minimum duty ratio for a given internal clock frequency is $r=3f/q_l$. Then, the averaged current consumption per second due to the LEDs is

$$P_{11}(q_l) = r(C_r + C_i) = 3f(C_r + C_i)/q_l$$

The current consumption of the microprocessor in terms of q_l can be expressed as following:

$$P_{12}(q_l) = aq_l + b$$

where the coefficients a and b can be empirically acquired. The total averaged current consumption of the LED circuit is

$$P_1(q_l) = 3f(C_r + C_i)/q_l + aq_l + b$$

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

$$dP_1/dq_l = -3f(C_r + C_i)/q_l^2 + a = 0$$

Namely,

$$q_l^* = (3f(C_r + C_i)/a)^{1/2}$$

In the prototype ring sensor, in order to generate as smooth piecewise constant waves as possible, the sampling and holding frequency is set to $f=1000$ (Hz). Also, two point-type LEDs are used for each of red and infrared emissions, and the current consumption of these LEDs is specified as:

$$C_r=2.333 \times 10^{-3} \text{ A}, C_i=0.5 \times 10^{-3} \text{ A}$$

In the ring sensor, we use a 14-bit microprocessor (model 16C711) of Microchip. The coefficients a and b of the microprocessor were empirically obtained as

$$a=1.96 \times 10^{-6}, b=3.226 \times 10^{-4}$$

From these parameters, we get the optimized internal clock frequency as

$$q_l^* = 65850.02 \text{ Hz}$$

The minimized current consumption is

$$P_1(q_l^*) = 0.29 \times 10^{-3} \text{ A}$$

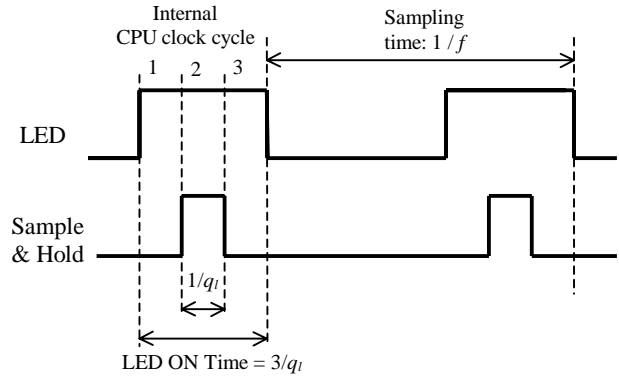


Figure 5: CPU clock cycles and time scheduling of an LED and sample & hold

RF transmitters

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 second microprocessor. The transmission protocol is the standard RS-232. The power-consuming part of the digital RF transmitters 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 significantly by minimizing the width of each 1-bit. Since the ring sensor is transmitting the data in the standard RS-232 protocol, the width can be reduced simply by increasing the baud rate of the RS-232. However, a high baud rate of the RS-232 requires a high clock speed for the microprocessor, which results in large power consumption. Similarly to the previous case, we derive a power budget of the transmission circuit and optimize the power consumption in terms of the clock frequency.

Let us define the key parameters of the power budget as follows:

- q_i : internal clock frequency of the second microprocessor (Hz)
- d : baud rate of the RS-232 transmission (bps)
- n : number of the sample points to be transmitted per second (Hz)
- m : averaged number of high bits to be transmitted per second (bps)
- C_t : total current consumption of the transmission circuit

Transmission of one bit needs at least one command instruction, taking one internal CPU clock cycle. Namely, the fastest baud rate for a given clock frequency is $d=q_i$. In the standard RS-232 protocol, five high bits are transmitted on average per sample point (one byte) including START bit, resulting in $m=5n$. Therefore, the averaged total time that the transmission circuit are active is $m/d=5n/q_i$. The averaged current consumption per second due to the transmission circuit is

$$P_{t1}(q_i) = 5nC_t/q_i$$

Since the microprocessor for the transmission is the same as that for the LED circuit, the current consumption of the microprocessor in terms of q_i can be expressed similarly as:

$$P_{t2}(q_i) = aq_i + b$$

The total averaged current consumption of the transmission circuit is

$$P_t(q_i) = 5nC_t/q_i + aq_i + b$$

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

$$dP_t/dq_i = -5nC_t/q_i^2 + a = 0$$

Namely,

$$q_i^* = (5nC_t/a)^{1/2}$$

In the prototype ring sensor, 30 points are sampled and transmitted from each of the two piecewise constant waves, accounting for $n=60$. Also, the current consumption of the transmission circuit on the ring sensor is specified as:

$$C_t=4.0 \times 10^{-3} \text{ A}$$

From these parameters, we get the optimized internal clock frequency as

$$q_i^*=24740 \text{ Hz}$$

The minimized current consumption is

$$P_t(q_i^*) = 0.129 \times 10^{-3} \text{ A}$$

Total Power Consumption

The other electric components of the ring sensor include multiple op-amps and switches for amplification, sampling and holding of received signals. These components are carefully selected for low current consumption and these circuits are optimally designed. The total current consumption of these components was found to be 0.126×10^{-3} A. Therefore, the total averaged current consumption of the ring sensor per second after the minimization is 0.545×10^{-3} A.

The power saving algorithm saves the power consumption of the ring significantly compared with the original system, where $r=0.5$, $d=600$ bps, and $q_i=q_t=8000$ Hz. As shown in Figure 6, the total current consumption was reduced to 14 % of the ring sensor without the power saving algorithm. The power saving of the transmitter circuit was the most significant (2.4%) while the LEDs could also reduce its power consumption to 9 %.

The above optimization method, while already reducing the power consumption significantly, can reduce the power consumption even more by using more efficient optical and electrical components. The current components, although selected carefully, still consume power substantially, limiting the life of a battery. For example, using a tiny battery cell of 220 mAh such as DL2032 of Duracell, which is currently used, the ring sensor can operate only for 16.81 days continuously without being replaced. Our target is to find more power-efficient microprocessors, op-amps, LEDs and transmitter, and reduce the current consumption to 0.152×10^{-3} A so that a patient can wear the ring sensor for two months without replacing the battery.

4. Conclusions

In this paper, a ring sensor for twenty-four hour patient monitoring 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 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.
- Estimation of the patient's location using a combination of a global receiver and multiple local receivers.

The issue of power saving for miniaturization of the ring sensor has been addressed and the power saving algorithm has been developed. it was shown that the power consumption was reduced to 14 % by the algorithm.

[6] M. Yamashita, K. Shimizu, and G. Matsumoto, "Development of a Ring-Type Vital Sign Telemeter," Biotelemetry XIII, 1995

References

[1] J. M. Schmitt, G.-X. Zhou, and J. Miller, "Measurement of Blood Hematocrit by Dual-Wavelength Near-IR Photoplethysmography," SPIE Vol. 1641, 1992

[2] J. C. Veraart, A. M. Van Der Kley, and H. A. M. Neumann, "Digital Photoplethysmography and Light Reflection Rheography," J. of Dermatol Surg Oncol, Vol. 20, 1994

[3] K. K. Tremper, S. J. Barker, "Pulse Oximetry," Anesthesiology, Vol. 70, 1989

[4] J. P. Welch, R. DeCesare, and D. H. Hess, "Pulse Oximetry: Instrumentation and Clinical Application," Respiratory Care, Vol.35, No. 6, June, 1990

[5] K. Ikeda, A. Watanabe, and M. Saito, "A Vital Sign Sensor for Elderly People at Home," Biotelemetry, Vol. 11, 1991

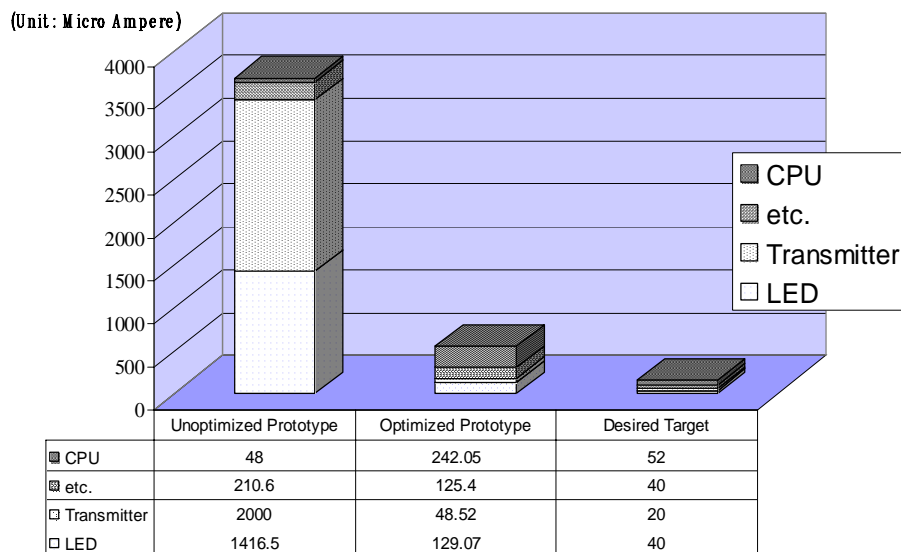


Figure 6: Power Consumption chart of the ring sensor by components