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Development of the ring sensor for healthcare automation

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Abstract

This paper presents the development of a miniaturized telemetered ambulatory monitoring device in a ring configuration. The device, called ring sensor, is worn by the patient at all times, hence the health status is monitored 24 hours a day. The ring is equipped with LEDs and photo detectors where the technology of pulse oximetry is implemented for monitoring pulse waves and blood oxygen saturation. The measured data are transmitted to a computer through a digital wireless communication link and the patient health status is analyzed continuously and remotely. Any trait of abnormal health status and possible accidents is detected by analyzing the sensor data. Detailed descriptions of the hardware and the software of the ring sensor including a noise protection algorithm will be presented. Also, unique features of the 24 hour patient monitoring system using the ring sensor will be discussed. ©2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: Wearable sensor; Continuous monitoring; Healthcare automation; Telemedicine; Elderly care

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 of an abrupt change of the patient health condition 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 non-compliant 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 telemetered wearable patient monitoring device in a ring configuration. Fig. 1 shows a conceptual diagram of the ring sensor. The ring 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 24 hours a day.

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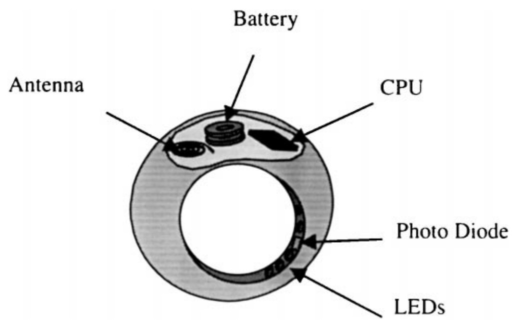

Fig. 1. Conceptual diagram of the ring sensor.

The ring sensor, however, is inevitably susceptive to a variety of motion and ambient light artifacts. The pulse wave signals from the optical sensors are often distorted by the noise so significantly that even the pulse rate cannot be calculated from the signals. To capture the pulse rate even from the noisy signals consistently, we have developed an efficient algorithm using a signal correlation method, in which periodic signals such as pulse waves can be reconstructed from the original signals contaminated by a random noise.

In this paper, we provide detailed descriptions of the hardware and software of the ring sensor. Also, the algorithm to capture the pulse rate from distorted pulse waves is presented with an experimental verification. Unique features of the 24 hour patient monitoring system using the ring sensor will be discussed at the end.

2. Concept of the ring sensor

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 24 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. 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 an optoelectric sensor. Subsequently, a variety of simple cardiac and circulatory disorders may be detected by monitoring arterial blood flow at the finger base.

3. Hardware description

To demonstrate the concept, we have developed a prototype ring sensor. Fig. 2 shows a photograph of the prototype ring sensor and Fig. 3 shows a block diagram of the ring sensor. In this prototype, LEDs with two different wavelengths, red and near infrared, as well as a photodiode are imbedded in the ring facing inwardly. The red and infrared 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 an RF wave through the standard RS-232 protocol. The whole process is scheduled and controlled by a single microprocessor on the

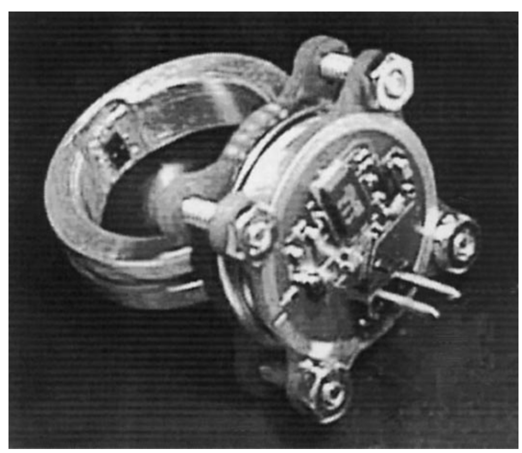

Fig. 2. The photograph of the finger ring sensor.

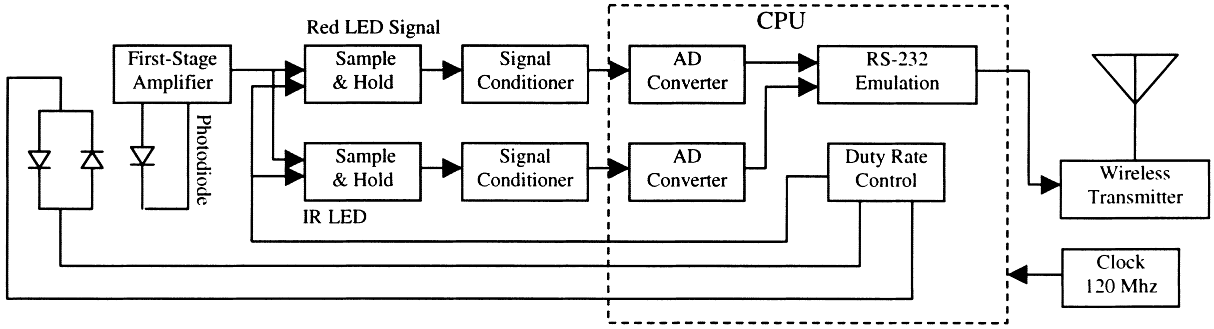

Fig. 3. Block diagram of the ring sensor.

ring. The description of each component is provided as follows.

3.1. Package

The ring sensor consists of a ring with LEDs and a photodiode, a four-layer printed circuit board (PCB) for signal processing, another four-layer PCB for wireless transmission, and two batteries. The signal processing and the wireless transmission were separated to reduce severe interference between the two functions. Two batteries are sandwiched between the two PCBs to supply the power to the two circuits. It has been found that the two circuits have to be powered separately to eliminate signal interference. I/O connections are distributed on the edge of the boards, providing the connections for power supplies, LEDs and programming. Four screws are used in the four ears on the boards to provide mechanical fixtures for the boards. All the circuitry on the boards are protected by optical epoxy after fabrication and debugging.

3.2. LEDs and photodiode

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

3.3. 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 an 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.

3.4. 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 infrared 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 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.

3.5. Signal conditioner

The signal conditioning part is composed of filters and amplifiers. Since the signal from the first stage amplifier is weak in a millivolt range, it must be amplified 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 low pass filter circuit. The low pass filter cuts off most of the frequency components higher than 20 Hz. Also there is a simple high pass filter circuit composed of a resistor and a capacitor that removes DC components. We used die-form integrated chips and wire-bonding-style resistors whose size is on the order of 20 by 40 mm.

3.6. 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 an RS-232 form for transmission. Since the CPU is one of the major components of power consumption, it has to be chosen carefully. For this purpose, we chose a PIC16C711 from Microchip. This CPU has two channels of embedded A/D converter, and 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 extremely 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 do not use this function since a much higher clock speed is necessary to obtain a satisfactory baud rate for the RS-232 generator, which will result in more power consumption.

3.7. 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 an RF wave by the microprocessor. The transmitter is simply an 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

Transmitted waveforms from the ring sensor are received and analyzed by a home computer. The technology of pulse oximetry [4] is implemented on the computer to monitor the patient's pulses and blood oxygen saturation continuously. Although the signal is already filtered and refined by the analog signal conditioner in the ring sensor, it still contains high frequency noises due to ambient light sources and motion artifacts. For example, Fig. 4(a) shows a steady photoplethysmogram without having any artifact, whereas Fig. 4(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 the hardware low pass filter.

In general, human pulse waves are periodic signals with relatively low frequencies and the noises from motion and ambient light are random or high-frequency signals. Considering the nature of these signals, we have developed an efficient algorithm of capturing the original pulse waves from a noisy photoplethysmograph by applying the autocorrelation method. The autocorrelation method is a very powerful tool in catching a periodic signal buried in random signals. Fig. 5 shows the flowchart of the signal processing software. Transmitted signal from the ring sensor first passes through the low pass filter. This filter mainly removes the relatively high frequency noises higher than 5 Hz including 60 Hz frequency component of the room light. The filtered signal then goes through the autocorrelation function. With this process, most of the non-periodic components are removed from the original signal and only periodic components of relatively low frequency will survive as the pulse waves. The autocorrelation function works as a kind of smoothing factor. The detailed algorithm of the autocorrelation method is presented as follows.

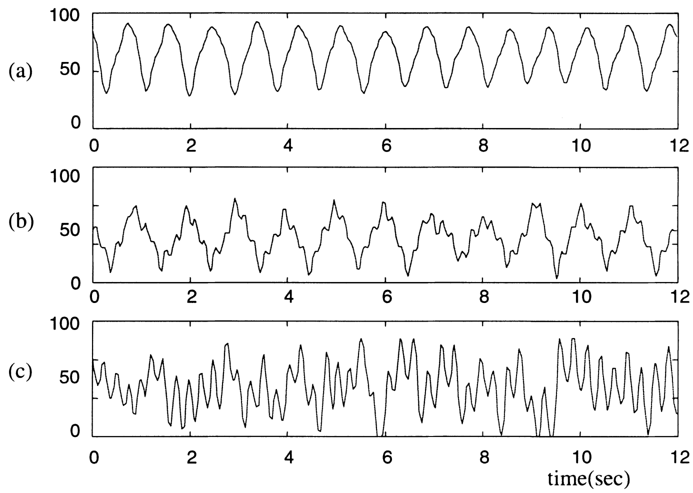

Fig. 4. Various signals detected by the ring sensor.

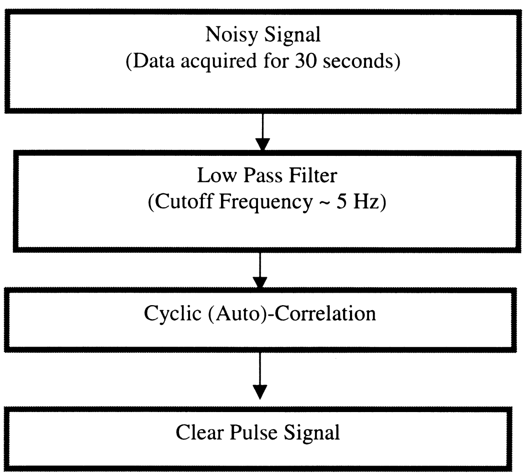

Fig. 5. Flowchart of the signal processing on the ring sensor.

The time-average of a discrete random signal $x[n]$ is defined as

$$\langle x[n]\rangle \equiv \lim_{N\to\infty}\frac{1}{2N+1}\sum_{n\to -N}^{N} x[n]. \quad (1)$$

The autocorrelation function is defined as follows:

$$R_x[k] \equiv \langle x[n]x[n-k]\rangle = \langle x[n]x[n+k]\rangle. \quad (2)$$

The autocorrelation function of a periodic signal with period N is also periodic with period N. On the contrary, for a signal having no periodic component, the autocorrelation function with a relatively large lag k approaches the square of the mean.

$$R_x[k+N] = R_x[k] \text{ (periodic)}$$
$$\text{if } x[n+N] = x[n] \text{ (periodic)}, \quad (3)$$

$$R_x[k] \approx \mu_x^2 \text{ (const.)} \quad \text{if } x[n] \text{ is non-periodic.} \quad (4)$$

This means that the autocorrelation function of a non-periodic signal does not contain AC component with a certain value of k whose absolute value is larger than zero as long as the sampling frequency is high enough relative to the frequency of the signal. For example, if we sample with 1 kHz, and take data for 30 s (total data points is 30,000), the autocorrelation of the non-periodic signal becomes almost constant with a relatively large value of k such as $k = 1000$.

Now let us consider the crosscorrelation function. A crosscorrelation function is defined as

$$R_{xy}[k] \equiv \langle x[n]y[n+k]\rangle = \langle x[n-k]y[n]\rangle. \quad (5)$$

If $x[n]$ and $y[n]$ are two sinusoidal waves with different frequencies, the crosscorrelation function of those two signals is zero by orthogonality, which means that they are uncorrelated.

We can say that if $y[n]$ is a non-periodic signal (which means the frequency is zero) with zero mean, the crosscorrelation of a periodic signal $x[n]$ and $y[n]$

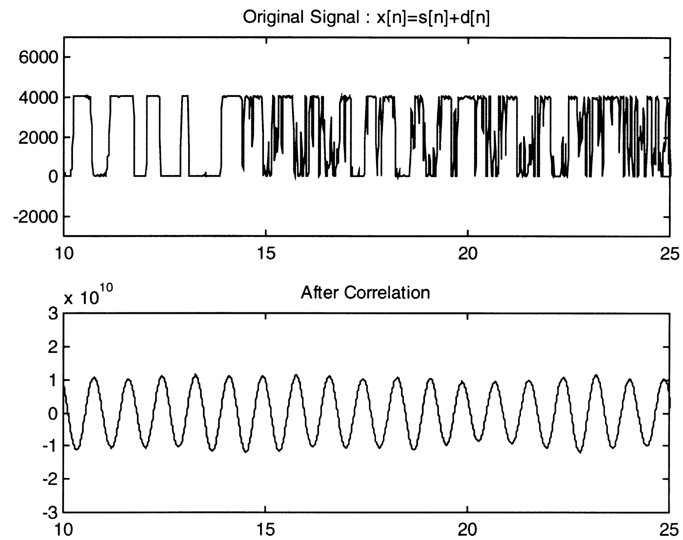

Fig. 6. Original ring sensor signal and the result after the autocorrelation processing.

becomes zero. If the signal $y[n]$ is a non-periodic but not a zero mean, the crosscorrelation function becomes a constant. This means that the crosscorrelation of $x[n]$ and $y[n]$ does not have any AC component.

$$\text{If } y[n] \text{ is non-periodic}, \quad R_{xy}[k] = \text{const}. \tag{6}$$

On the other hand, the crosscorrelation of two sinusoidal waves having the same frequency is a sinusoidal wave at the same frequency. This case is similar to the case of Eq. (3).

The signal received by the ring sensor can be expressed as follows:

$$x[n] = s[n] + d[n], \tag{7}$$

where $s[n]$ is a periodic heartbeat signal and $d[n]$ is a non-periodic noise. The autocorrelation function of $x[n]$ is

$$\begin{aligned} R_x[k] &= \langle x[n]x[n+k]\rangle \\ &= \langle (s[n]+d[n])(s[n+k]+d[n+k])\rangle \\ &= \langle s[n]s[n+k]\rangle + \langle d[n]s[n+k]\rangle \\ &\quad + \langle s[n]d[n+k]\rangle + \langle d[n]d[n+k]\rangle \\ &= R_s[k] + R_{sd}[k] + R_{ds}[k] + R_d[k]. \end{aligned} \tag{8}$$

From Eq. (4), we can see that $R_d[k] \approx$ constant, and $R_{sd}[k]$ and $R_{ds}[k]$ are also constants according to Eq. (6) since $d[n]$ is a non-periodic signal. From Eq. (3), $R_s[k]$ contains the frequency of the original signal $s[n]$, and this $R_s[k]$ is the only AC component in $R_x[k]$. In the ring sensor application, this means that only the periodic heartbeat signal survives and non-periodic noises are removed by applying the autocorrelation function.

$$R_x[k] = R_s[k] + \text{const}. \tag{9}$$

5. Validation of the device

To demonstrate the ring sensor and establish the validity of the noise protection algorithm, we conducted experiments. Fig. 6 shows the original signal detected by the ring sensor and the signal processed by the autocorrelation technique. The original signal was obtained from the ring sensor when the hand was tightly clenched. As seen from the figure, the original signal was significantly distorted and contaminated with the noise. The signal even shows the state of bad saturation because of the hand grip. But after the correlation technique was applied, the signal was arranged in a neat shape and the high frequency noise was also removed. Although the exact "pulse shape" could not be recovered, it can be seen that the periodic component of the detected signal was recon-

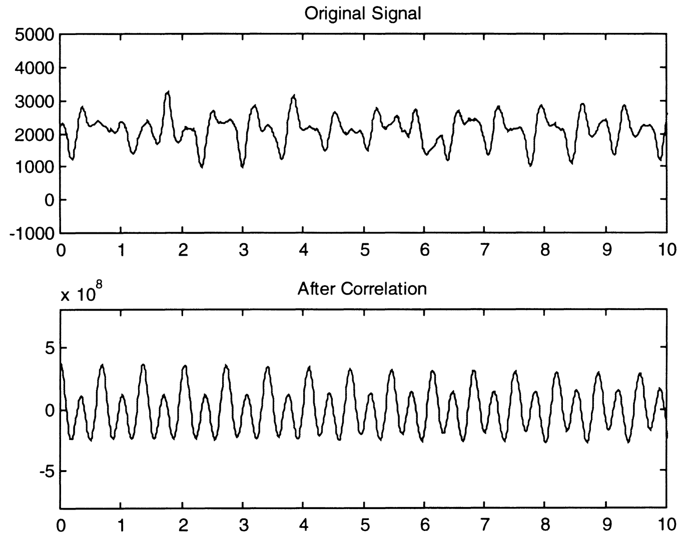

Fig. 7. Autocorrelation function showing the second peak of the pulse wave.

structed by the autocorrelation method, which means that we can estimate the pulse rate even in the worst situation.

The above example does not explicitly show the second peak, the nature of human arterial plethysmographs, after the autocorrelation filter since the periodic characteristic of the second peak in the original signal was not apparent and was seriously ruined by the noise. The next example shows that even the second peak can be reconstructed as long as the original signal contains a clear behavior of the second peak as shown in Fig. 7.

As we can see in the experimental results, the autocorrelation function method has intrinsic limitation in reconstructing the minor peaks in the waveform. This is mainly due to the averaging effect of correlation. We can better reconstruct the waveform by using a shorter window for slicing the signal at the expense of effective noise reduction. If the noise is relatively less, then it is possible to reconstruct the original waveform with higher resolution. On the contrary, we have to stay with getting only the exact pulse rate in the case of severely low SNR. In our ring application, the main emphasis of which lies in continuous heartbeat monitoring, the pulse rate itself will have a great clinical importance.

6. Twenty-four hour patient monitoring system

Using the prototype ring sensor, a 24 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 photoplethysmograms and sends a warning signal to a telenursing center through a telecommunication channel such as internet if any abnormality is detected.

The ring sensor and the 24 hour patient monitoring system have the following distinctive features:

6.1. Photoplethysmograpy 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, i.e., 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.

6.2. 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.

6.3. 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 receivers: a global receiver and local receiver. The global receiver has a broader range of reception and covers almost the entire house. A local receiver has a narrower range and is 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 half an 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.

7. Conclusions

In this paper, a 24 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 analyzes the received data and discriminates 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 heartbeat 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 heartbeat 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.

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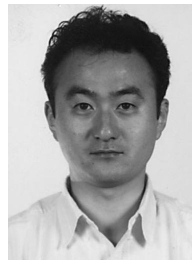

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