

Artifact-Resistant, Power-Efficient Design of Finger-Ring Plethysmographic Sensors

Part II : Prototyping and Benchmarking

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Abstract-- A miniaturized, telemetric, photoplethysmographic sensor called a “ring sensor” for long-term monitoring is presented. A prototype ring sensor is designed and built based on the power budget analysis and the artifact-resistive attachment method. It is verified through experiments that the ring sensor is resistant to interfering forces and acceleration acting on the ring body. Benchmarking tests with FDA-approved photoplethysmograph and EKG reveal that the ring sensor is comparable to those devices in detecting beat-to-beat pulsation despite disturbances.

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

I. INTRODUCTION

The ring sensor is a miniaturized, telemetric, monitoring device worn by a patient as a finger ring. The ring encapsulates photoplethysmographic, pulse oximetry combined with wireless communication and miniaturization technologies. 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. [1][2]. In this paper, a prototype ring sensor was built and tested based on the power budget analysis and the artifact-resistive method developed in [3]. It will be shown that the device meets diverse and conflicting requirements, including compactness, motion artifact reduction, and minimum loading effects. Its benchmarking tests with FDA approved PPG and EKG will show the validity of the technology.

II. PROTOTYPING OF THE RING SENSOR

A. Description of the Basic Circuitry

The basic circuit configuration of the ring sensor is a standard photoplethysmographic circuit combined with a wireless transmitter. There are a single photodiode and LEDs of two different wavelengths, red and near infrared, involved in the circuit. The output from the photodiode is amplified and conditioned at the first stage operational amplifier. While the red and infrared LEDs are alternately turned on and off, the signal from the first stage op-amp is sampled by the two sample-and-hold circuits at different timings in order to obtain the reflected light intensity from each LED. Each channel of the signal is conditioned and converted to a digital signal with an AD converter. Using the standard RS-232 protocol, the two channels of digital signals are transmitted via a RF transmitter.

This circuit is a standard one, but the whole system is designed and operated for low-power consumption. Since the battery cell is the dominant factor determining the dimension and weight of the device, large batteries cannot be used for the ring sensor; hence reduction of power consumption is critically important for miniaturizing the sensor. Each component has to be selected for low-power consumption and the whole system must be operated for minimum power consumption. The microprocessor coordinates the whole operation so that reliable measurement is performed with minimum power.

B. Description of Mechanical Structure

Figure 1 shows a prototype of the ring sensor. Details of this design are:

- ◆ A miniaturized sensor unit is attached to the inner ring whose mass is almost negligible. This sensor unit is a small circuit board (5mm × 5mm × 0.8mm) that contains two light emitting diodes and a photodetector. As we use point-based light emitting diodes and a subminiature photodetector, this sensor unit weighs only 0.79 grams.
- ◆ The main circuit board and batteries, which are heavy and bulky in comparison to the sensor unit, sit on the outer ring. The main circuitry consists of many small elements, most of which are in a surface mount or bare die form. Although the size and weight of the components used are generally small and light, the total mass of this circuit board is not negligible, 3.68 grams. In addition, the button type batteries used for providing power to the circuitry are relatively heavy, 6.31 grams. These components sit on the surface of the outer ring facing outward.
- ◆ The inner ring floats inside the outer ring. When a patient wears the ring, both rings are put on the same finger. Since the outer ring covers the inner ring, the external force is born by the outer ring and does not directly act on the inner ring. Although the outer ring may be dislocated due to the external force, the sensor unit on the inner ring can be held stably, since there is no direct mechanical connection between the two rings except for a few thin wires. The two rings are mechanically decoupled.

III. EXPERIMENT

The prototype ring sensor is now evaluated experimentally. There are several issues that need experimental verification and evaluation.

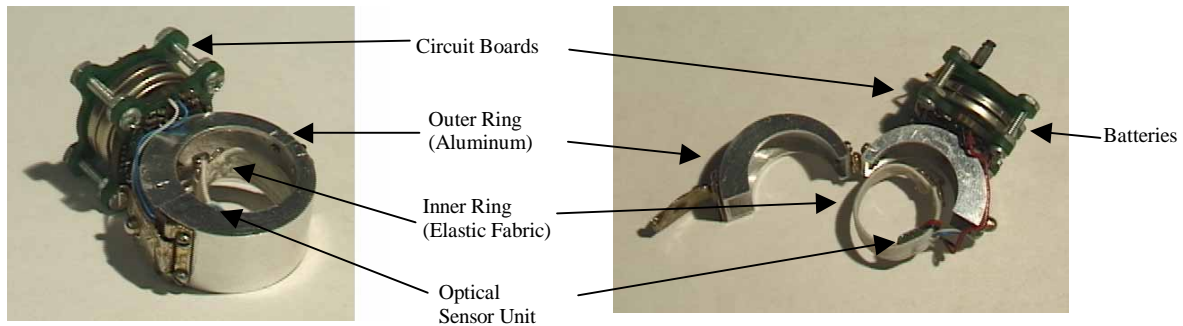


Figure 1 : Isolating ring sensor designed for motion artifact minimization

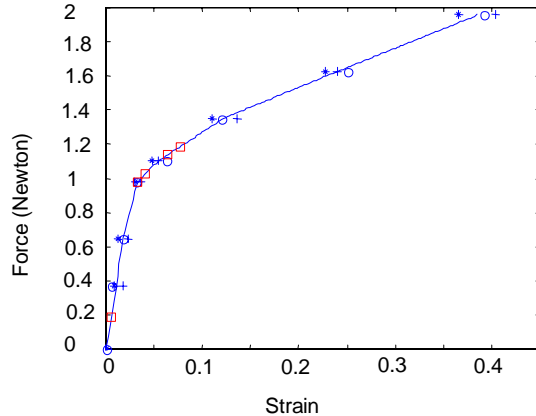


Figure 2 : Experiment of tension-strain characteristics of inner ring band

A. Adjustment of Inner Ring Tension and Skin Pressure

The inner ring must hold the sensor unit securely and stably with an appropriate pressure against the finger skin. It is known that pressurizing the tissue increases the pulsation amplitude of blood vessels and thereby provides a better signal to noise ratio. However, as the skin pressure increases, the possibility of necrosis and blood occlusion increases. As mentioned previously, the pressure with which the sensor unit is attached to the skin must be tuned to a proper level by making a trade-off between these two conflicting requirements.

The inner ring must apply this pressure and maintain the desired level despite disturbances. The thickness of the finger base, however, varies for various reasons. The inner ring must therefore have some compliance to accommodate the pressure in the face of variation in the finger conditions. To this end, a polyester braided elastic band (70% polyester, 30% rubber, from Rhode Island Textile Company) was used for the prototype inner ring. This has been used for underwear in the apparel industry, and proven to be comfortable to wear. This material has a unique nonlinear elasticity: the spring constant is high for small strain, while it becomes very low beyond a certain limit. Therefore, it allows the inner ring to keep the tension almost constant despite a wide range of finger diameter change.

Figure 2 shows the experiment of the tension-strain characteristics of the polyester braided elastic band. Note that the slope is steep up to 4% of strain, i.e. high Young's modulus. Beyond this limit, the slope lowers to 1/15 of the initial steep slope. Therefore, in this range of large strain, the

tension of the inner ring does not vary much, even though the finger diameter varies. In other words, the sensitivity of the inner ring tension to the finger diameter change is very low. The pressure applied to the skin surface is given by

$$P = \frac{2T}{Dw} \quad (1)$$

where P is skin pressure, T the tension, D the diameter of the elastic band, and w the width of the inner ring, i.e. the elastic band. Combining the tension-strain characteristics in Figure 2 and the above equation, the skin pressure can be obtained based on the unsprung length of the inner ring belt and the finger diameter. This skin pressure showed a good agreement with actual measurements using the micro pressure gage.

B. Benchmarking

The new ring sensor was benchmarked with other FDA-approved devices. An electrocardiogram (EKG) from AD Instruments Pty, Ltd. (NSW, Australia) and a standard fingertip photoplethysmograph from IBS Corp. (MA, USA, FDA-approved) were used for benchmarking. The three devices were attached to a subject at the same time, and data were recorded simultaneously. The fingertip PPG was attached to the tip of the middle finger of the right hand, while the ring sensor was to the base of the middle finger of the left hand. The EKG probes were attached to the standard three points of the body.

Two benchmarking tests were conducted. First, the FFT power spectrum of the ring sensor waveform was compared with those of EKG and the fingertip PPG. Second, the heart rate obtained from the ring sensor signal was compared with those of EKG and the fingertip PPG. Both benchmarking tests were repeated for different conditions with respect to external loads and skin pressure.

Waveform Power Spectrum

Figure 4 shows the waveforms of the three devices recorded simultaneously and their FFT power spectra. The subject was a 29-year old healthy male. The FFT power spectra were computed for the waveform data recorded for 10 seconds, i.e. approximately 16 pulses. The first peak frequencies of the three spectra are exactly the same, 1.50 Hz, while the second peak around 3 Hz is within 1.6 percent of variation. There is no significant difference between the fingertip PPG and the ring sensor power spectra.

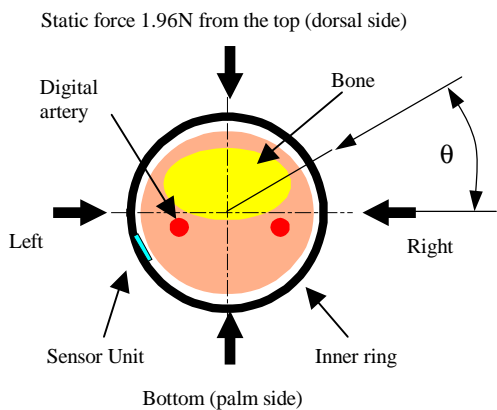


Figure 3 : Static force experiment

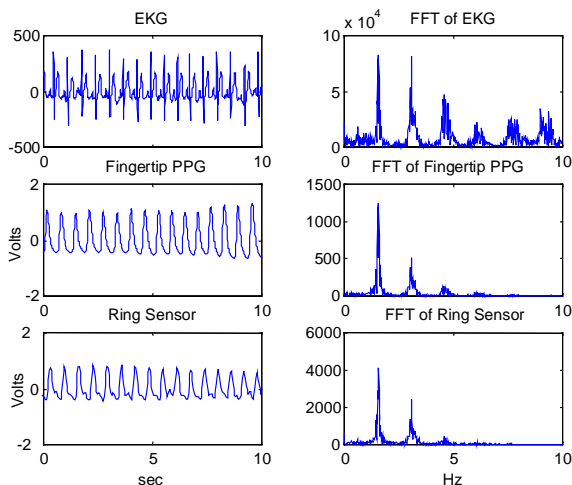


Figure 4 : No external static force with skin pressure of 75 mmHg. "Fingertip PPG" is the photoplethysmograph at the fingertip using FDA-approved device (IBS Corp)

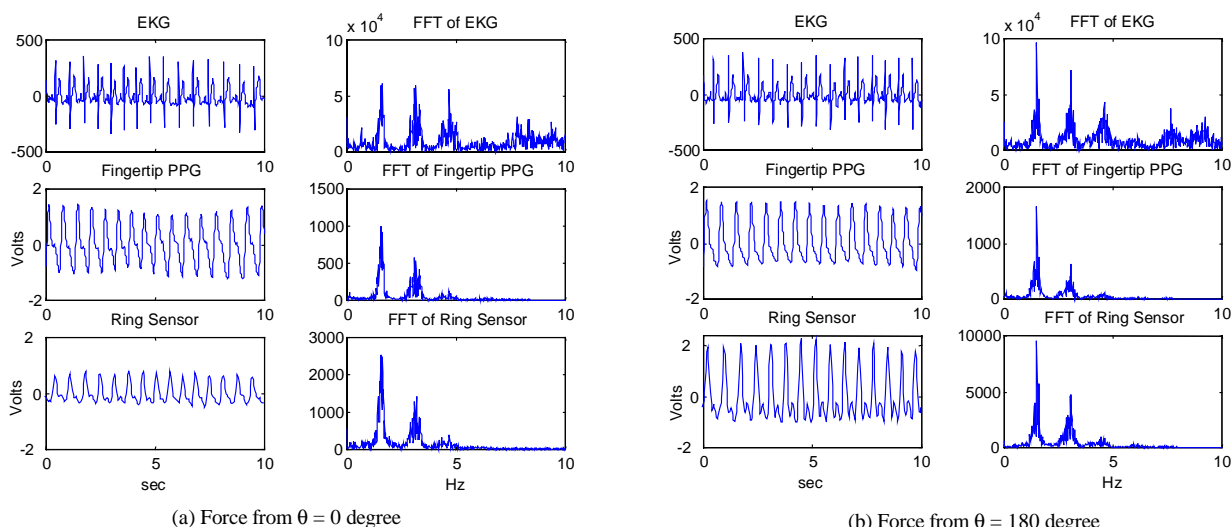


Figure 5 : Static force experiment with 75 mmHg skin pressure. "Fingertip PPG" is the photoplethysmograph at the fingertip using FDA-approved device (IBS Corp)

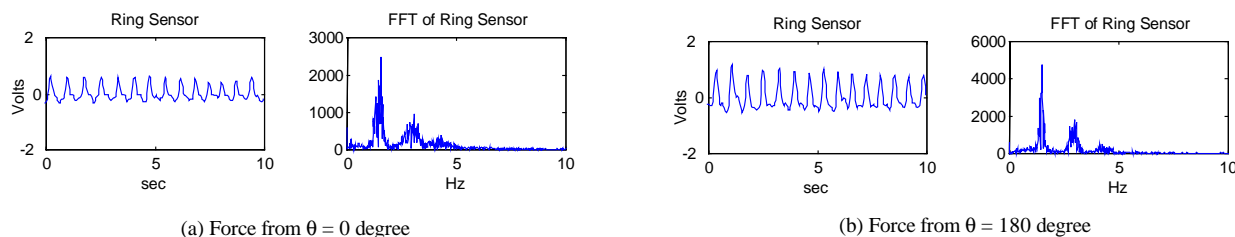


Figure 6 : Static force experiment with 11 mmHg skin pressure.

The ring sensor must work despite interference due to contact with the environment surface, as discussed previously. To verify that the ring sensor can function properly even under static loads, the benchmarking test was repeated with external forces applied to the ring body as shown in Figure 3. Figure 5 shows the waveforms and power spectra of the ring sensor with a static force of 1.96 N applied to the outer ring from different directions. The EKG and fingertip PPG data are shown for comparison. Note that no external load was applied to the EKG and fingertip PPG, although some variations are

apparent in these data¹. While the amplitude of the ring sensor signal varied depending on the external load, the first and the second peak frequencies in the power spectra remained the same. The ring sensor's peak frequencies have no significant difference from those of the EKG and fingertip PPG, although the static load was applied to the ring sensor.

The skin pressure used for the above experiments was 75 mmHg, an acceptable pressure that won't incur local ischemia, as was suggested by [4]. To evaluate robustness of

¹ This kind of variation in EKG and fingertip PPG measurements is common.

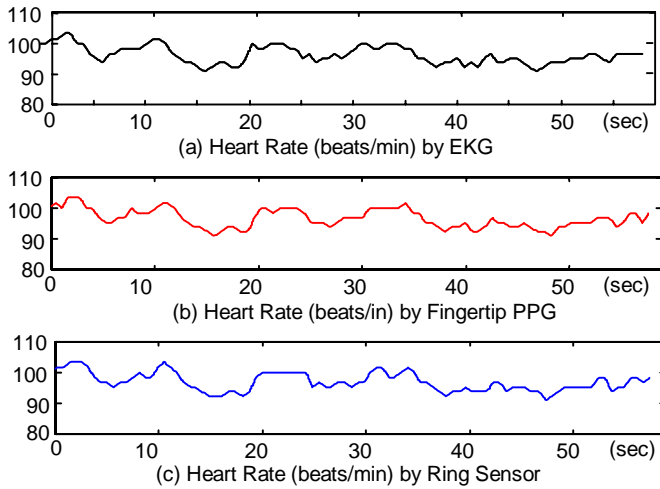


Figure 7 : Heart rate monitored by EKG, Fingertip PPG device, the Ring Sensor

measurement in relation to skin pressure, experiments were repeated for a low skin pressure. Figure 6 shows waveforms and power spectra of the ring sensor when the skin pressure was lowered to 11 mmHg. The ring sensor still shows a consistent result with regard to the first peak frequency, although the static load of 1.96 N was applied from two directions. However, the waveforms were completely distorted when the hand was shaken. Therefore, waveforms tend to be susceptible to hand motion, as the skin pressure is lowered. As long as the ring sensor is used under stationary conditions, however, the skin pressure can be lower than 75 mmHg.

Heart Rate Monitoring Tests

The consistent detection of the first peak frequency demonstrated in the above experiments implies that the ring sensor can be used as a beat-to-beat heart rate sensor. Figure 7 shows the beat-to-beat heart rate measured for the same subject when a light cardiac load was applied. The heart rate was determined by detecting the base point in each pulse and measuring the interval between adjacent base points. For benchmarking, the EKG and fingertip PPG data were simultaneously recorded, and the heart rate was extracted from each signal in the standard manner of beat-sampling technique [5]. The experiment was conducted for 60 seconds. The variation of heart rate has close correlation with that of the EKG and fingertip PPG. Table 1 shows the root mean square errors of the beat-to-beat heart rate, compared with the EKG and fingertip PPG. For a skin pressure of 75 mmHg, the difference between the ring sensor and EKG is 1.23 beats per minute, while that with the fingertip PPG is 1.22 beats per minute. For comparison, the table also shows the root mean square error between the EKG and fingertip PPG. The discrepancy between the ring sensor and the other two is as small as that of the EKG and fingertip PPG. When the skin pressure was lowered to 11 mmHg or increased to 146 mmHg, the discrepancy tends to increase. Nevertheless, the error is as small as 1.6 beats per minute. These results clearly show that the ring sensor's accuracy is comparable to those FDA-approved devices and that the ring sensor can function even under static load and acceleration with a proper skin pressure.

Contact pressure	EKG and Ring Sensor	Fingertip PPG and Ring Sensor	EKG and Fingertip PPG
11 mmHg	1.44	1.39	0.83
75 mmHg	1.23	1.22	0.77
137mmHg	1.41	1.27	0.96
146mmHg	1.60	1.54	0.94

Table 1 : RMS error (beats/min) of the heart rates from the ring sensor compared with those from EKG and fingertip PPG device

IV. CONCLUSION

An artifact-resistive and power-efficient design of ring sensors has been tested and evaluated.

- A prototype ring sensor has been built, and tested. Experiments have verified that the ring sensor can detect beat-to-beat pulsation in the face of interfering force and acceleration acting on the ring body.
- The prototype ring sensor has been benchmarked with FDA-approved PPG and EKG. The FFT spectral analysis has revealed that the ring sensor is comparable to the FDA-approved devices with regard to the first and second peak frequencies of the power spectra. Furthermore, the ring sensor is comparable to those devices for the measurement of beat-to-beat pulse variation. The discrepancy is less than 1.23 pulses per minute.

These experimental data and benchmarking tests have demonstrated that the ring sensor can be used as a wearable sensor for long-term, continual monitoring of patients in the home and other environments.

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Poster Session: TH-FXH-75 Poster Session: IV Bioinstrumentation and biosensors - Biochem. and Optical Sensors and Biosensors

Track: 22 Bioinstrumentation and Biosensors

Short Paper Available

A miniaturized, telemetric, photoplethysmographic sensor called a “ring sensor” for long-term monitoring is presented. The ring sensor is a miniaturized, telemetric, monitoring device worn by a patient as a finger ring. The ring encapsulates photoplethysmographic, pulse oximetry combined with wireless communication and miniaturization technologies. A prototype ring sensor is designed and built based on the power budget analysis and the artifact-resistive attachment method called “isolating ring design.” It is verified through experiments that the ring sensor is resistant to interfering forces and acceleration acting on the ring body. The prototype ring sensor has been benchmarked with FDA-approved PPG and EKG. The FFT spectral analysis has revealed that the ring sensor is comparable to the FDA-approved devices with regard to the first and second peak frequencies of the power spectra. Furthermore, the ring sensor is comparable to those devices for the measurement of beat-to-beat pulse variation. The discrepancy is found to be less than 1.23 pulses per minute despite disturbances. These results clearly show that the ring sensor’s accuracy is comparable to those FDA-approved devices and that the ring sensor can function even under static load and acceleration with a proper skin pressure