Doctoral Thesis Proposal

Design and Optimization of an Artifact-Resistive Wearable Photoplethysmographic Device : The Ring Sensor

by

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I. 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 a patient's 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 noncompliant patients such as demented elderly people is highly in demand.

Among the widely accepted physiological indices, vital sign and oxygen saturation rate are two important indicators of health condition. These two indices can deliver abundant information of the health condition of a patient provided that they can be monitored continuously. Although the existing ECG and pulse oximetry machines are clinically accepted for measurement of the indices, they still fail to guarantee comfort for wearers due to their excessive size and weight. 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. Figure 1 illustrates a conceptual diagram of the miniaturized ring sensor. This sensor is equipped with optoelectric components that allow for long-term monitoring of a 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 condition. 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.

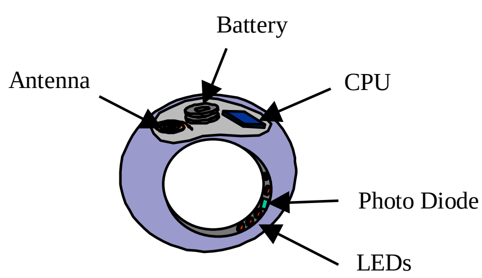


Fig 1: Conceptual Diagram of the Ring Sensor

The ring sensor, however, is inevitably susceptive to a variety of motion and ambient light artifacts. For example, in highly accelerated motions of the patient, the inertia force causes the optical sensor unit to move or slide on the skin surface, and, as a result, the optical sensor measurement would be distorted or even ruined completely. Even a static external force causes a similar distortion of the measurement due to the relative displacement of the sensor to the finger. In addition, ambient light is another major source of artifact on the optical measurement. These kinds of external disturbances can seriously degrade the quality of measurement of the ring sensor.

There have been many attempts to analyze and reduce the influence of motion on the photoplethysmography. Although many researchers attempted to quantify the movement artifact in pulse and oxygen saturation measurements [5][6], those attempts did not help to understand the nature of the motion artifact since they were based on the input-output matching approach using signal processing techniques without an in-depth understanding of the physiological effects of movement. Thus, it was not possible to conduct an optimization of the design parameters of the photoplethysmographic device for the best quality of measurement.

Currently, the most common existing techniques for dealing with artifacts are based on signal processing methods, which perform continuous real time conditioning of the received signal [7]. Another common method is to identify and reject corrupt photoplethysmographic signals by comparing pulse features with a predetermined ideal, while yet another method controls the power levels of multiple light sources dynamically in such a way that any optical coupling effects are balanced between a pair of signals and can thus be removed. Nevertheless, all of these methods are based on modifying the received signal and do not attempt to eliminate or diminish the influence of the sources of artifacts.

Another important issue of this type of wearable sensor is the possible necrosis of finger tissues caused by local ischemia or vascular congestion. To attain a stable photoplethysmographic signal, it is necessary to apply a certain amount of pressure on the skin surface for the duration of monitoring as many pulse oximeters do. With the constant, prolonged pressure at the finger base, the arteriovenous and cutaneous circulation in the finger will be obstructed, and possibly result in subsequent tissue sphacelation. Numerous studies have dealt with the effect of ischemia on tissue and other types of pressure sores, and a few of them discuss critical pressure and duration [8][9]. These researches found that an inverse relationship exists between the critical pressure and duration. Some researchers also investigated the ischemic hyperemia on the finger, which may eventually result in tissue injury [10]. Therefore, the ring sensor should be designed not to administer excessive pressure on the finger in order to be used for long term monitoring.

In this research, an optimized design of the ring sensor for motion artifact minimization will be presented and implemented. To examine the sources of motion artifact, mechanical and optical interaction between the sensor and finger will be analyzed through an opto-physiological model. A smart design named “isolating ring sensor” will be presented and its design parameters will be optimized referring to the opto-physiological model to minimize the influence of the motion artifact and prevent possible necrosis of tissue by excessive pressure. In addition, appropriate signal processing methods will be studied and implemented to obtain a stable measurement from the ring sensor.

II. Proposed Research

It has been explained in the introduction that the motion artifact is a crucial issue in attaining stable and accurate measurement. Administration of appropriate pressure on the skin surface is another important issue. To cope with these issues, it is essential to gain a profound understanding of the physiological, optical and mechanical behavior of the whole system.

In this thesis, I propose that a mathematical model including the optical and mechanical interaction between the finger and sensor should be developed and verified by experiment, and an optimization process of the ring sensor design for motion artifact minimization should follow based on the opto-physiological model. This proposed research addresses the following three issues.

1. *Designing the basic structure of the ring sensor for motion artifact minimization and initial prototyping*

Since the concept of the ring sensor is novel and original, it is necessary to build an initial prototype to confirm the feasibility of the device. The device fabricated at this stage need not be optimized for said issues. Any smart design idea for motion artifact rejection will be tested and implemented in this initial prototype, but the parameters will not be optimized. Oxygen saturation measurement, LED intensity control, and power saving by sleep mode will be implemented. If possible, a field test of the ring sensor will be conducted with the cooperation of a hospital.

2. *Mathematical modeling of the finger photoplethysmography and experimental verification.*

To articulate and analyze the influence of each movement, a mathematical model of the finger photoplethysmography will be developed. The main feature of the model will be the integration of multiple domains such as the ring mechanics, finger tissue kinematics, digital arterial wall dynamics and biomechanical optics. Especially, the nonlinear behavior of the arterial wall to external pressure, which is the basis of the oscillometric method of blood pressure measurement, will be intensively addressed. Also, the optical property of the finger tissue will be profoundly discussed. The resultant opto-physiological model of the finger and the ring sensor will allow for numerical simulation of the influence of mechanical displacement of the finger on photoplethysmographic signals. This model will elucidate the response of the physiological system to external pressure induced by the ring sensor under movement or static forces. Experimental verification of the model will be conducted with optical sensors and pressure transducers.

3. *Integrated Mechanism / Filter Design and Optimization*

With the systematically built mathematical model, the relationship of finger photoplethysmography and motion will be studied in detail and an optimized design for minimum motion artifact will be proposed. The major design parameters to be optimized will include width and inner diameter of the outer ring, tension of the inner ring, light source intensity and position of the sensor. In particular, the tension of the inner ring will be determined to take into consideration vascular congestion induced by the pressure administered on the finger. Through theoretical modeling and experiments, the effect of each design parameter will be investigated and ultimately optimized to achieve the minimum influence of motion artifacts. As it is hard to completely eliminate the motion artifact in terms of hardware design, appropriate technique of signal processing that effectively rejects the motion artifact will be accompanied.

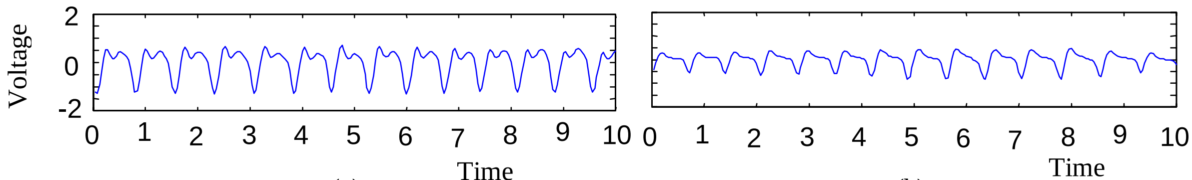
III. Preliminary Research

1. *Designing the basic structure of the ring sensor and initial prototyping*

Several prototypes of the ring sensor have already been developed by the author. The first prototype was equipped only with fundamental features for waveform monitoring. Fig 2(a) shows a photograph of the first prototype.

(a) (b)

Fig 2 : (a) First prototype (b) Second prototype : Isolating ring sensor with motion artifact minimization



(a) (b)

Fig 3 : (a) Photoplethysmogram from a stretched finger
(b) Photoplethysmogram from a bent finger

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 alternate 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 a frequency of 25 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 ring.

In the development of the second prototype, in order to guarantee stable and clear signal measurements, a smart design of double ring configuration was employed that can minimize the influence of the sources of mechanical and optical disturbances on signal detection while avoiding excessive pressure on the finger. The main idea of this unique design called “isolating ring sensor” is to separate the optical sensor unit from most of the inertia of the device. This separation can be achieved by employing two rings (an inner ring and an outer ring) which are mechanically independent of each other [11]. The inner ring is made up of an elastic material to maintain necessary pressure on the skin, while the outer ring is composed of a solid material such as aluminum to sustain the mass of the circuit boards and battery. Fig 2(b) shows a photograph of a prototype of the isolating ring sensor. An exemplary waveform monitored by the isolating ring sensor appears in Fig 3. Fig 3(a) is the waveform detected from a stretched finger, while Fig 3(b) shows the waveform from a bent finger. The variation of amplitude depending on the posture of the finger is the consequence of pressure-induced arterial dynamics which will be elucidated by the mathematical model.

2. *Mathematical modeling of the finger photoplethysmography and verification by experiment.*

To explain the dynamics of finger-based photoplethysmography, the model should include descriptions of the finger in both cross section and along the longitudinal direction. Fig 4 illustrates a cross-sectional view of a finger. The cross section of the finger is assumed to be a circle in the absence of external forces. There are two digital arteries in the finger, and they are both positioned at a distance h_0 away from the center of the finger. The tissue is considered as compliant material with stiffness k_t. There is also a layer of capillaries of thickness t beneath the skin. To alleviate sensitivity of the photoplethysmographic signal variation due to movement of the finger, a compliant material of stiffness k_b is attached inside the solid ring. A light source (LED) and a photodetector are located on the compliant material inside the solid ring. When an external force is applied to the ring, it moves in a certain direction at an angle α by a certain relative displacement d. Because of this movement, the pressure at the contact point increases and the locations of the digital arteries relative to the optical elements (LED and photodetector) change, which leads to a variation in the photoplethysmographic signal. At the same time, deformation of the finger surface occurs and the cross section of the finger is no longer a circle. Due to this deformation of the tissue, the pressure applied to each of the two digital arteries also changes, which results in a change in the volumetric pulsation of the blood vessel. In addition, the volume of the capillaries also changes due to the change in the pressure. The capillaries occlude more easily than the digital arteries since the internal pressure of the capillary is much lower than that of the arteries. The pulsating signal of the photoplethysmograph is induced by the volumetric change of the digital arteries and capillaries due to the change in the blood pressure. Combining photon migration theory and geometry of the finger cross section, it is possible to describe the finger photoplethysmography with a mathematical formulation [12].

To describe the finger photoplethysmography of the isolating ring sensor, it is necessary to model the finger in the longitudinal direction as well as in cross section. Fig 5 illustrates an idealized schematic of the finger with the isolating ring sensor. An external force exerted on the outer ring does not directly apply to the point of measurement. To predict the variation of the photoplethysmogram generated by the external force, pertinent modeling of the finger tissue and fluidic reaction in the blood vessel is essential. A two-parameter model such as the Vlasov model may be employed to explicate the behavior of the finger tissue.

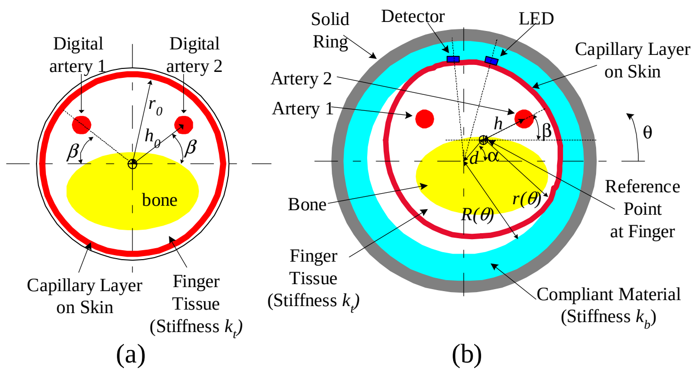


Fig. 4: (a) Uncompressed finger under no external force (d=0). (b) Finger compressed by the ring due to an external force.(d>0)

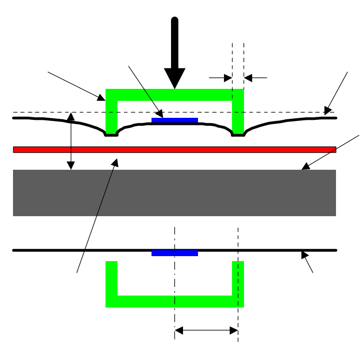


Fig 5 : Longitudinal modeling of finger and isolating ring sensor

IV. Time Table

Tasks	1999				2000				
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Prototyping	■	■	■						
Mathematical Modeling & Experimental Verification		■	■	■					
Design Optimization					■	■	■		
Thesis Writing								■	■

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