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Improving the Design of Blood Pressure and Blood Saturation Monitors

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***Abstract*—**A blood pressure monitor or sphygmomanometer can be either manual or automatic, employing respectively either the auscultatory method or the oscillometric method.

The manual version of the sphygmomanometer involves an inflatable cuff with a stethoscope adopted to detect the sounds generated by the arterial walls to measure blood pressure in an artery.

An automatic sphygmomanometer can be effectively used to monitor blood pressure through a pressure sensor, which detects vibrations provoked by oscillations of the arterial walls.

The pressure sensor implemented in this device improves the accuracy of the measurements taken.

***Keywords*—**Blood pressure, blood saturation, sensors, actuators, design improvement.

I. Introduction

AN automatic blood pressure monitor inflates a cuff surrounding an arm with sufficient pressure to prevent blood flow in the local main artery.

This pressure is gradually released until the blood begins to flow through the artery, the measurement of which determines the systolic pressure. Instead, the measurement accomplished when the blood flows without any possible obstructions determines the diastolic pressure. Pulse rate is also recorded at this stage.

The resulting measurements are displayed on a liquid-crystal display (LCD), time/date-stamped and stored in non-volatile memory [1].

II. Implantable Optical Sensors for Subcutaneous Blood Pressure Monitors

Blood pressure monitoring may be achieved through a closed loop system, which involves a blood pressure sensor and a drug pump, which automatically regulates the blood pressure level.

A subcutaneous blood pressure monitor involves a minimally invasive system that, once implanted, uses pulse transit time to measure blood pressure.

The pulse wave is detected through a photoplethysmographic signal, accurately recorded directly on the subcutaneous muscular tissue [2].

Pulse wave detection via photoplethysmographic is carried out by a flat 20mm x 6mm optoelectronic pulse oximeter functioning in reflection mode.

The optical sensor can be implanted adopting minimally invasive methods, by applying a small incision in the skin, constantly monitoring blood pressure on a daily basis.

A. Blood Saturation Monitors or Oxygen Saturation Monitors

A blood saturation monitor or oxygen saturation monitor, also named as oximeter, is a noninvasive method of recording and examining the percentage of hemoglobin, which is saturated with oxygen and changes in blood volume in the skin.

Being successfully applied in pulse oximetry, it is useful if patient's oxygenation turns to be unsteady, such as cases of emergency, operations, either recovery or intensive care, to establish whether oxygen supply is needed or not [3].

Furthermore, with the recent improvements in technologies, the blood saturation monitor has been proved very useful to check the health status of pilots in unpressurized aircraft.

Readings of oxygen saturation, chemically represented by SaO_2, may range from 0 to 100%; however, typical values in a healthy adult are registered to be from 94% to 100%.

B. Typical Sensors Applied to Blood Saturation Monitors

A blood saturation monitor involves a probe sensor linked either to a patient's ear lobe or to a finger, which is connected to a computerized unit.

This unit shows the oxygen saturation and it produces a sound for each heartbeat.

Indeed, an automatic blood saturation monitor achieves more accurate measurements than the ones recorded through measuring the percentage of dissolved oxygen straight away through a blood sample [4].

C. Bluetooth-Integrated Sensor for Blood Saturation Monitors

The Bluetooth fingertip oxygen monitor enables clinicians to remotely control patients' pulses and check the values recorded for oxygen saturation.

This device also allows patients to examine the status of their health through online health records and home telemedicine system [5].

An oximeter with integrated wireless radio and a touch screen interface has been successfully implemented in the newest clinical applications which allowing doctors to instantaneously monitor any patients within the facilities of the hospital.

D. Optical Fibre Sensor for Blood Saturation Monitors

An optical fibre system for recording the percentage of oxygen saturation in the blood present within a tissue has been initially applied to brain tissue and now successfully

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implemented in further monitoring applications.

This optical sensor allows the blood saturation monitor to detect the percentage in oxygen saturation and blood volume in the central nervous system of patients who may typically recover from neurological surgery or neural injuries, such as intracerebral hemorrhages [6].

Sources of light and a photodetector have to be coupled to optical fibers to obtain a very small probe to penetrate a cranial bolt, scientifically classified as a two-wavelength optical fibre photoplethysmography system.

In such a way, the estimations of blood volume and oxygen saturation can be obtained even more accurately than the ones taken by using the most advanced automatic blood saturation monitors.

III. Actuators for the Two Kinds of Automatic Blood Pressure Monitors

The two main kinds of automatic blood pressure monitors are the upper-arm and the wrist models.

The upper-arm model has a cuff, which has to be placed on the upper arm and connected by a tube to the monitor.

Fig. 1 A digital automatic upper-arm blood pressure monitor [7]

The wrist model has a smaller overall dimension and the whole unit has to be wrapped around the wrist. This is a much more space-critical design.

Fig. 2 A digital automatic wrist-cuff blood pressure monitor [8]

Some upper-arm models require manual inflation of the cuff, which does not return as accurate values as the ones, which may have been recorded through the automatic model. However, most of the upper arm and all wrist blood pressure monitors have fully automatic inflation [9].

IV. Functionality of the Sensors Applied to Blood Pressure Monitors

A sensor acts as a transducer device, which converts a measured mechanical signal into an electrical signal.

A pressure sensor converts pressure into an analogue electrical signal, like a voltage output or current output, which can be easily measured. There are different types of pressure sensor. The sensor that is the most cost effective and functional to our application is named as Force Collector Type [10].

This type of digital pressure sensors uses a so-called Force Collector (e.g. diaphragm, piston) to measure strain. The most common technology for pressure measurements is strain gage transducer, which consists of two elements an elastic material that deforms when pressure is applied and an electrical device, which detects the deformation.

The elastic component can be in different shape and sizes relatively to the sensing principle and range of pressure to be measured the most common one is diaphragm, a thin and flexible film. Instead, the most typical configuration for the electrical device employed in this digital pressure sensor is called Wheatstone Bridge.

The elastic material and the electrical device are combined together to create a sensor pressure.

When pressure is applied to the pressure sensor, it causes the diaphragm to deflect and this phenomenon produces a strain to the gage. The strain will consequently generate an electrical resistance change corresponding to the pressure.

V. Pressure Sensors for Digital Blood Pressure Monitors

A digital blood pressure monitor uses a combination of pressure sensor for sensing arterial wall vibrations, analogue signal-conditioning circuitry, microcontroller and a LCD display.

Its function is based on the oscillometric method, which implies the measurement of the pressure variation.

The cuff is inflated until the blood flow in main artery is blocked (a pressure greater than the systolic), then, the pressure inside the cuff is gradually decreased. The reducing pressure applied on the artery allows blood to flow through it and sets up a detectable vibration in the arterial wall. The systolic measurement is determined at this particular stage [11].

When the restriction is removed and the blood starts flowing smoothly through the artery at the usual pulses, the diastolic measurement is taken. The vibrations are transferred from the arterial wall, through the air inside the cuff, into the transducer.

Because the output by pressure sensor is too small, the amplifier is used to increase the output signal of the pressure sensor. The output signal from the amplifier will be sent to a microcontroller. The microcontroller will process the signal and translate it. Eventually the LCD screen will display the reading of the blood pressure.

A. Estimates on Magnitudes, Sensitivity and Accuracy of Sensors Applied to Blood Pressure Monitors

Further design improvements in the force-transducing component resulted in the new H-shaped design, which integrates the sensing piezoresistor in the beam itself.

The pressure sensors with a strain gauge on the beam contribute in achieving non-resonant pressure sensitivity between 0.8 μV/V/mmHg and 0.9 μV/V/mmHg, whilst sensors with the piezoresistor integrated in the beam is 5 μV/V/mmHg.

The resonance frequency is determined by sensing the amplitude of the beam vibration either electrically, by using a piezoresistor, or optically. The resonant pressure sensitivity measures 3%/bar circa [12].

The best noise-limited pressure resolution was proved to be 0.9 Pa (0.007 mm Hg), when a response time of 200 ms circa was recorded.

B. Functionality of the Sensors Applied to Blood Saturation Monitors

Pulse Oximetry (SpO_2) is a device that measures the percentage of molecules of haemoglobin in the arterial blood saturated with the oxygen. The sensor is put over the thin part of the body. Within the SpO_2 sensor, there is a light sensor containing two LEDs as light sources, which emit red and infrared light, on one side and a light sensitive photo-detector on the other one.

The lights shine through the body tissues in particular sequences. First, the SpO_2 activates the red light and it passes through the body tissues and gets to the detector on the other side. Then, the red LED light goes off, whilst infrared LED goes on. The detector records the amount of LED lights plus room lights that fall on it [13].

Eventually, when both lights are off, the only light that falls on the detector is room light. At this stage, the amount of the room light is known, thus the sensor can subtract it from LED lights to measure the amount of red and infrared lights seen by the detectors [14].

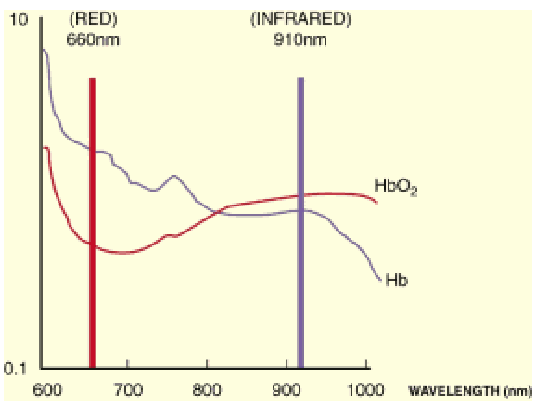

Fig. 3 The two LEDs used as light sources in the Pulse oximetry [15]

The quantity of light received by the detector reveals the percentage of oxygenated blood concentration. Oxygenated haemoglobin absorbs more red lights, which have a wavelength of 660nm and deoxygenated haemoglobin absorbs more infrared lights with wavelength of 910nm. By comparing the red and infrared lights, the equipment can calculate the amount of oxygen in the body.

The pulse oximeter uses Beer's and Lambert's law that describes the concentration and path length effect on the absorption of the light. According to this law, the light, which goes through the sample, should go straight through, but because blood contains different objects, e.g. white cells, it causes the light to spread instead of going in a straight line [16].

In order to use Beer's and Lambert's law a "calibration graph" is used. This graph is produced from numbers of healthy humans, whose copy is inside the pulse oximeter. When performing its calculation, the computer refers to calculation graph and corrects the final reading displayed.

VI. The LED Driver Circuit

The signal needs to be multiplexed (when several analogue and digital signals are combined in a medium signal), because in the pulse oximeter there is only one photo detector and two different wavelength. The SpO_2 uses a GPIO-controlled analogue multiplexer (General Purposes Input/Output), which is a generic pin on a chip that can receive a signal from sensors, which allows selecting the light to be sampled [17].

A PWM signal (Pulse-Width Modulation) is employed to simulate an analogue signal from a digital one and control the density of the LEDs. A Led driver circuit is used to provide enough energy for LEDs to work, by supplying constant current level at the correct voltage level.

A. The Sensor

The sensor is connected to the board through a connector. The photo-detector generates an output current because of the light absorption. Then, the current passes through a voltage converter in order to be filtered, amplified and converted to a voltage [18].

The signal now is multiplexed to its specific filter and amplification stage (either red or infrared). By now, the signal is treated and, because the signals are very small, they need to be amplified in order to be detected by microcontroller analogue/ digital converter.

B. Estimates on Magnitudes, Sensitivity and Accuracy of Sensors Applied to Blood Saturation Monitors

During low perfusion pulse oximetry can overcome the limitations of conventional pulse oximetry and may offer up to 97% sensitivity and 95% specificity for alarms in motion and low perfusion conditions [19]. Commercial pulse oximeters are generally designed to handle a wide range of pulse rates (i.e., between 18–300 bpm and, equivalently, 0.3–5 Hz in frequency).

The accuracy of most oximeters is approximately 2% and the medical use of pulse oximetry does not require precision beyond this level.

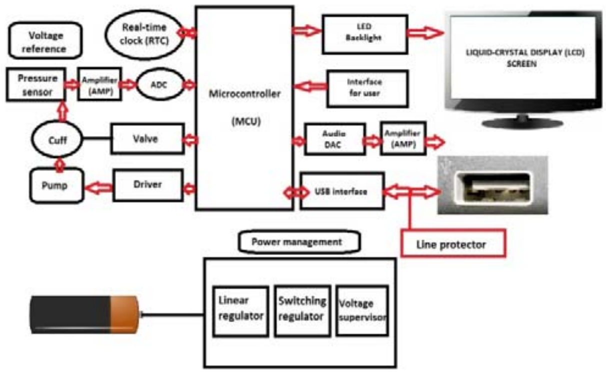

Fig. 4 Block diagram on the basic signal processing involved in a blood pressure monitor – Detailed version

A pressure cuff and pump, along with a transducer, are deployed to measure blood pressure and heart rate in three phases: inflation, measurement and deflation. The block diagram depicted above also includes LCDs, interface for the user, real-time clock (RTC), power management and USB interface [20].

The system, as outlined above, includes:

Data processing and memory — Digital measurement of blood pressure and heart rate are accomplished by the microcontroller (MCU). Measurement results are stored in flash memory as a data log that can be uploaded to a computer via USB or wireless connection.

User Interface — it enables the user to check how the pressure has been recorded and read the results as displayed on a liquid-crystal display (LCD) screen.

Sensor interface — it allows the processor to monitor both cuff inflation and deflation, and detect blood pressure whose signal is amplified by instrumentation amplifiers and digitized by the analogue-to-digital (ADC) converter.

Power Management — it converts the input power from the alkaline or rechargeable batteries to run different blocks of functional operations.

The block diagram referred to the blood saturation monitor is very similar to the one depicted above, but to be sketched accurately, it needs to take into account the following specific design constraints and considerations:

- An inverting resistor-feedback configuration is typically deployed used with the gain amplifier in the signal chain and it needs to drive the output swing down to or below the ground, as large feedback resistor values may drive extreme output swings with small changes in light intensity due to the sensitivity level of the circuit [21].
- As generally it requires ultra-low power consumption Ti's buck-boost converters are implemented to support extended batteries life and provide 96% efficiency and precise measurements.

VII. Pressure Sensors for Blood Pressure Monitors – Prices and Specifications

Fig. 5 Commercially available pressure sensor for blood pressure monitors [22]

A. Description

The pressure sensor required for invasive blood pressure monitoring is a fully piezoresistive silicon pressure sensor. The sensor is typically applied to automatic blood pressure monitors and can be placed in a customer's disposable blood pressure housing.

The sensor meets the requirements outlined in the specifications for blood pressure transducers prescribed by the Association for the Advancement of Medical Instrumentation (AAMI).

The pressure sensor is composed of a sensing element placed on a ceramic substrate with thick-film resistors. A plastic cap, linked to the ceramic substrate, allows connecting to the customer's assembly and protects the sensing element. A dielectric gel can be put on the top of the sensor to guarantee both electrical and thermal isolation.

These pressure sensors are fabricated in a 10x12-element array on a ceramic substrate, thus ending up with 120 units. The products are shipped either in anti-static containers or on a tape and reel.

B. Specifications

- ❖ Multiple configurations;
- ❖ Calibrated according to AAMI specifications;
- ❖ Low cost disposable design;
- ❖ Solid-state piezoresistive and disposable blood pressure sensor;
- ❖ Pressure entry on the top side;
- ❖ Compatible with automatic blood pressure monitors equipment;
- ❖ Integral dielectric gel for electrical and thermal insulation;
- ❖ Fully tested.

C. Prices

- $15-28 per piece – Silicon Blood Medical Pressure Sensor [23];
- $143 - Vernier Blood Pressure Sensor [24].

The most technologically advanced pressure sensors that can be implemented to blood pressure monitors can be found on the website listed at [25], even though, for obvious reasons related to the costs of the materials employed, they have been discarded from our detailed analysis.

D. Considerations and Specifications on Sensors Applied to Blood Saturation Monitors

The ideal sensor for blood saturation monitors has to have an application site that has good perfusion, generates movement as naturally as possible, is comfortable for the patient and allows an easy application.

If a finger sensor is too large, it may slip slightly off so that the light source partially covers the finger. This condition, called optical bypass, causes incorrect readings.

Fig. 6 Pediatric finger sensor [26]

If a finger is inserted too far into the sensor, it may be squeezed by the sensor, which causes venous pulsation.

Neonates tend to have movement artifact in their fingers, so choose a toe or foot sensor.

Fig. 7 Toe sensor for neonates [27]

Fig. 8 Foot sensor for neonates [28]

VIII. Fingertip Pulse Oximeter

A. Specifications

Fig. 9 Fingertip pulse oximeter [29]

- Primary Function: Finger pulse oximeter and heart rate monitor;
- Colours: Blue, white;
- External material: Hard moulded ABS plastic;
- Display mode: LED display;
- SpO_2: 35 - 99%;
- Pulse Ratio: 30 - 250BPM;
- Resolution: 1% for SpO_2, 1BPM for pulse ratio;
- Accuracy: +/- 2% (70% - 99%), unspecified (<70%) for SPO2, +/- 2BPM or +/- 2% (select larger) for pulse ratio;
- Power Requirements: Two AAA alkaline batteries (not included);
- Battery consumption: Two AAA 1.5V, 600mAh alkaline batteries can be continuously used as long as 30 hours;
- Optical Sensor: Red light wavelength 660nm, infrared wavelength 910nm;
- Dimension: L: 58 x W: 32 x H: 34 (mm);
- Large LED display for use in a wide range of light or dark environments;
- Pulse-strength display bar indicates relative perfusion at the measurement site;
- Fast, reliable and accurate on patients from pediatric to adult;
- One-button keypad for ease of operation and auto power shutdown after 8 seconds when not in use conserves batteries;
- Low battery indicator flashes when 30 minutes of battery time remains.

B. Prices

- Prices range from £30.49 to £290 and the model can be chosen from [30].
- Prices range from £17.95 to£ 295 by Pulmolink Ltd, Redwood House, Canterbury Road, Charing, Kent, TN27 0EU.

For further details on prices and specifications on blood saturation monitors, please see [31], [32] and [33].

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