Pulse Oximeter Project

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1 Introduction

These notes outline an Electrical Engineering senior level project for measuring blood oxygen level and monitoring heart rate, the *Pulse Oximeter* or *Photoplethysmograph*. Blood oxygen content is an important indicator of human patient health and during anaesthesia [1].

An overview of the theory of the pulse oximeter is in references [2], [3] and [4]. The *sensor head* of a pulse oximeter contains two light-emitting diodes and a photodetector. One LED emits in the visible range, the other in the infared. Each LED is illuminated in turn. The detector may be placed to detect light transmission (through a finger, for example) or light reflection from skin. The ratio of the detected light signals is proportional to the blood oxygen level. It is best if the same detector can be used for both visible and infared signal detection.

References [5], [6] and [7] describe various implementations of the pulse-oximeter and related circuits.

In teaching structure, these notes are a *guided design*, an intermediate engineering exercise with difficulty and risk between a structured lab exercise and a completely open-ended design. In this note we provide relevant sources of information and examples of other approaches to this design. We identify key design decisions and intermediate steps toward a final design.

2 The Project

A minimum level project will include optical detection of heart rate, which can be accomplished with one illumination channel as demonstrated in [5] and [6]. A more advanced level project will measure heart rate and blood oxygen level with two illumination channels.

3 Design Approach

In this section we outline a general approach to designing the system. As in most engineering designs, various design considerations interact. For example, in this project the *sensor optical design* and *sensor mechanical design* are inter-dependent. Consequently, you should be familiar with the entire sequence before starting, and you should be prepared for a certain amount of iteration and backtracking. Any backtracking is *much* easier at the paper design stage than once hardware has been constructed, so do as much design work and planning as possible before launching into construction.

3.1 Cardiac Signal

It is useful for this project to have some familiarity with the human cardiac signal. Normal heart rate is in the region of 220 beats per minute. The waveform has a complex shape [10] that should be preserved through sensor detection and signal processing.

Set up the WGM-101 waveform generator so that it is directly connected to the input of the DSO-101 oscilloscope. Load the generator with the ECG arbitrary waveform file. Set the generator to a frequency equivalent to the cardiac beat rate. Capture this waveform on the oscilloscope and store it for reference.

Use the *spectrum analysis* capability of the oscilloscope to determine the spectrum of the cardiac waveform. (It may be helpful for the spectrum measurement to scale the frequency upward.) Capture the spectrum and store it for reference. You should now have an idea of the frequency range of the ECG, which will be important for signal processing.

3.2 Identifying and Obtaining Parts

There are two approaches to finding parts for this project.

1. **Specify and Obtain** Check through various catalogues and identify suitable parts according to their specifications. Order those parts by phone or email. The Digikey and Mouser web sites are useful for this approach. Digikey provides overnight delivery to Toronto.

2. **Obtain and Specify** Obtain parts from various local sources: Creatron, Supremetronic, Sayal, Active-Tech, Active Surplus. Then determine the specifications from the vendor, by measurement or by tracking down the relevant datasheet on the web.

3.3 Sensor Optical Design

The sensor design is critical in the functioning of the overall system. Amplification or filtering can improve signal strength and signal-noise ration, but there must be a measureable signal to work with. In project management parlance, this is the *killer problem* that must be solved in the project to ensure success [9].

The project references show visible and infared LEDs as emitters. They also show a photodiode and CdS (cadmium sulphide) photo-resistive cell being used as detectors.

In general, the photo-resistive cell is more sensitive, that is, produces a larger signal for a given level of light. That makes them easier to work with since signal amplification is less critical. On the other hand, they are relatively slow devices and may have difficulty responding accurately to the cardiac pulse waveform. They are also broad-spectrum devices and respond to light in the visible spectrum but may have difficulty responding to infared illumination.

Photodiodes are much faster responding and have a narrower response spectrum. Particular photodiodes are available that respond to visible or infared illumination. This simplifies the filtering task. On the other hand, the output signal of a photodiode is much smaller than a photo-resistive cell.

When using a photodiode, it may be connected in the *photovoltaic* mode or *photocurrent* (reverse biased) mode. Photovoltaic mode may simplify power supply requirements, but either mode will work.

Issues that must be resolved are:

1. **Is the detector a good spectral match to the emitter?** This may be determined by examining the datasheets for the LEDs and detector and confirmed by experiment.

   To experiment, set up an LED so that it is pointing at the detector. Wire up the detector. The photodiode will require an op-amp circuit. A photo-resistor can be connected into a voltage divider. Monitor the detector output. Enable and disable the light path and determine the change in detector output.

2. **Will the detector respond rapidly enough to display the heart waveform?** Check the detector spec sheet to determine response time and relate that to the frequency of a cardiac waveform.

   Verify this as follows:

   Use the oscilloscope to set up the waveform generator output so that it is producing a unipolar waveform of several volts. Place a resistor of 1 or 2KΩ in series with the LED to limit current. Use this signal to drive the LED and display the waveform on Channel A of the oscilloscope.

   Connect channel B of the oscilloscope to the output of the detector and ensure that you are seeing the LED signal. Vary the frequency of the waveform generator and measure the output of the detector at various frequencies. Relate this to the frequencies in the cardiac waveform.

   For complete documentation of the sensor response, configure the waveform generator and oscilloscope as a *vector network analyser* [11], [12]. Set the analyser to sweep over the range of frequencies for a cardiac waveform. The VNA will record the amplitude and phase of the sensor signal over those frequencies. Save that result for reference.

3. **Will the emitter-detector combination produce a reliable signal?** The literature shows the LED - detector arrangement with either a transmissive path (through a finger, for example) or a reflective path (off the surface of skin.) The transmissive method seems more popular but either can be used.

   In a true engineering environment, we would develop a mathematical model of the light medium between the LED emitter and the detector and then validate that model with experiment. With the time constraints of this project, we must move directly to experiment.

   Using the setup from the previous step, insert a human finger into the light path and measure the detector output. There should be a small but measureable signal. Note any contaminating signals such as 60 or 120Hz interference from electromagnetic coupling or room light sources. If you are using a both a visible and infared LED, measure the detected signal for each source.

3.4 Sensor Mechanical Design

You will need to mount the LEDs and detector so that the optical path - reflection or transmission - operates correctly and reliably. Furthermore, it is desireable that the mounting system exclude ambient light. The mechanical design may influence the choice of the light emitter and detector packages. For example, surface-mount LEDs may be easier to incorporate into the mounting system than the traditional T 1-3/4 package.

The devices should be mounted so that their attached wiring has a mechanical strain relief. Flexing the wiring should not cause the device leads to flex. Use small-diameter stranded (not solid) wire to connect from the sensor head to the signal-processing electronics.

3.5 Output Data Display

A variety of output signals are possible, ranging in complexity.

- At a minimum, the Pulse Oximeter should flash an indicator LED on each heartbeat.
- The waveform is captured on the DSO-101 oscilloscope and downloaded to a host PC for further processing in a spreadsheet or other analysis program on a ’batch’ basis. The process is operated by hand to demonstrate that it is feasible.
- Host PC software processes incoming data on a ’real time’ basis without operator intervention, to display in a graphical user interface such variables as pulse rate and oxygen saturation content. This can be accomplished by modifying the existing Tcl/Tk host software or with a software package such as Labview or Matlab.

3.6 Signal Processing

The signal processing section prepares the pulse oximeter sensor signal for output data display.

For example, to trigger an indicator LED on each pulse the heartbeat pulses must be of sufficient and consistent amplitude and must not contain extraneous noise signals.

For data analysis, the signal must have a sufficient signal-noise ratio when captured by the digital oscilloscope, and must not be contaminated by noise.

Signal processing might contain any or all of the following functions:

- remove DC component
- remove out-of-band noise signals with bandpass filter
- amplify signal to well above oscilloscope minimum levels
- provide a suitable trigger threshold for a trigger indicator, midway between peak and valley points
- disable processing during artifacts caused by movement

3.7 Power Supplies

The power supply subsystem is an important component in the design. Its design is often left until all other aspects of the circuit are complete, That approach can force substantial rework of the design when it is found that the power supply is too expensive, too large or too complicated.

In this project, the power supply must provide power for the LED emitters and the signal processing circuitry. This circuitry can be powered from lab power supplies. However, since the development instrumentation is portable (WGM-101 waveform generator, DSO-101 oscilloscope or PocketLab unit) it makes most sense to provide power independent of the university lab equipment.

Fortunately, the voltage and current requirements are modest, so a simple power supply is sufficient.

Split Supply

The LED emitters operate from a single DC power supply, which is straightforward.

There are two approaches to power for the signal processing section: split supply operation and single supply operation.

Split supplies provide the traditional positive and negative voltages with a centre-tap ground. This keeps the op-amp circuitry simple but requires a dual supply.

The two supplies may be provided very simply by batteries (+/-9V, for example). However, they must be checked carefully to ensure that they are not discharged. There is no current limit, so a power supply short circuit will quickly discharge a battery and may destroy components.

Alternatively, an AC wall adaptor can be provided with two half-wave rectifiers. One half-wave provides a positive voltage, the other provides a negative voltage. Notice that most wall adaptors have a DC output, and this must be AC.

A DC wall adaptor can be used with an electronic circuit that produces an artificial centre tap ground. This type of circuit is shown in reference [6].

There are switching power regulators that will accept a single DC input and generate positive and negative voltages that are larger or smaller than the input. (Such as supply is used in the WGM-101 waveform generator.) However, they are probably excessively complex for this application.

Single Supply

Many modern op-amps are designed to operate from a single DC power supply. Generally, they will operate satisfactorily from a lower voltage than split-supply op-amps. However, this requires that the standard op-amp circuits for amplifiers, filters and so on be modified for single supply operation. Reference [13] has an extensive collection of single-supply opamp circuits.

Whatever op-amp circuits are used in this application, it is important to ensure that the common-mode input voltage is not exceeded, and that the output swing is not restricted by the power supply voltages.

If an unregulated wall adaptor is used, its output voltage will vary over a wide range. It may be desireable to regulate the voltage with a three-terminal regulator.

3.8 Biographies

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