Tufts University

Department of Electrical and Computer Engineering

EE21 - Electronics I W/lab

Lab 4

Pulse Oximeter Sensor Stabilization using Feedback Control

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1 Introduction

A pulse oximeter is a non-invasive medical device widely used in healthcare settings to monitor the oxygen saturation of a patient's blood and heart rate. These devices function by emitting light through the patient's body—typically a fingertip or earlobe—using an infrared LED. A photodetector opposite the LED measures the amount of light that passes through the body part, with variations in absorption during each heartbeat indicating changes in blood oxygen levels. This can used in various scenarios where a rapid or precise monitoring of an individual's respiratory status is critical, such as during surgery, in recovery rooms, and for patients with chronic respiratory or cardiovascular conditions.

This project focused on further refining pulse oximeter technology developed through this course by incorporating a feedback control mechanism by adjusting the intensity of the emitted light from an infrared LED based on variations in finger sizes among different patients. This aims to stabilize the voltage across the photodetector, ensuring consistent device operation across diverse patient demographics. Through the design, construction, and evaluation of a bias circuit for safely operating a Zener diode, the utilization of a MOSFET for LED current control, noise filtering and amplification by OpAmp, and the development of a system to compensate for variations in detected light intensity, we enhanced the device's adaptability and reliability in a clinical setting.

2 Background

2.1 Pulse Oximetry Overview

Pulse oximetry is a non-invasive diagnostic method used extensively in medicine to monitor the oxygen saturation (SpO2) of the blood and heart rate. This technique utilizes an infrared (IR) LED to emit light that passes through a peripheral part of the body, typically a fingertip or earlobe. A photodetector captures the light that has traversed the tissue. The variations in light absorption and transmission during each cardiac pulse reflect changes in blood oxygen saturation. As blood oxygenation varies with the cyclic inflow of oxygenated arterial blood, the device detects these fluctuations and computes the SpO2 level.

2.2 Key Components and Their Functions

2.2.1 Infrared LED and Photodetector

Infrared LED The IR LED in pulse oximeters emits light at two specific wavelengths: one in the red spectrum (around 660 nanometers) and one in the near-infrared spectrum (around 940 nanometers). These wavelengths are carefully selected to correspond to the distinct absorption characteristics of oxyhemoglobin and deoxyhemoglobin.

Oxyhemoglobin Absorbs more infrared light (940 nm) and less red light (660 nm).

Deoxyhemoglobin Absorbs more red light and less infrared light.

Light Detection Positioned on the opposite side of the emitting LED relative to the finger, the photodetector captures the light that passes through the tissue. Different amounts of red and infrared light are absorbed based on the oxygen levels in the blood, leading to varying intensities at the two wavelengths reaching the detector.

Signal Conversion The intensity of light detected at each wavelength is converted into an electrical signal. These signals reflect the varying light absorption properties of oxyhemoglobin and deoxyhemoglobin.

2.2.2 Signal Processing and Oxygen Saturation Calculation

DC Component (DC_Red and DC_IR): Represents the baseline level of light absorption by the tissue, independent of the pulsatile changes due to the heartbeat. This component includes absorption by all tissue elements, not just arterial blood.

AC Component (AC_Red and AC_IR): Represents the pulsatile changes in light absorption due to arterial blood flow. This component varies with each heartbeat and is influenced directly by the blood's oxygen saturation.

Calculation of Oxygen Saturation (SpO2):

$$R = \frac{\left(\frac{AC_{\text{Red}}}{DC_{\text{Red}}}\right)}{\left(\frac{AC_{\text{IR}}}{DC_{\text{IR}}}\right)}$$

AC_{Red} and AC_{IR} are the changes in intensity due to arterial blood pulses at red and infrared wavelengths, respectively. DC_{Red} and DC_{IR} are the baseline intensities at red and infrared wavelengths, respectively.

The color of blood plays a significant role in light absorption. Oxyhemoglobin, which gives blood a bright red color, reflects more red light and absorbs more infrared light. Conversely, deoxyhemoglobin, with a darker appearance, absorbs more red light and reflects more infrared light.

2.2.3 Filters and Signal Processing

To accurately measure the pulsatile signal that corresponds to heartbeats and thus to blood oxygen levels, the signal must be filtered and amplified:

- Low-Pass Filter (LPF): This filter is used to remove high-frequency noise that does not contribute to the measurement of the baseline oxygen saturation. It helps in stabilizing the DC component of the signal, which is crucial for accurate baseline readings.

- High-Pass Filter (HPF): This filter eliminates the DC components and isolates the pulsatile waveform which is synchronous with the heartbeats. This waveform variation directly correlates with arterial blood oxygen saturation.

Band-pass Filter Combines the functions of both high-pass and low-pass filters, allowing only a specific range of frequencies to pass. This is important in pulse oximetry to filter out frequencies that are not indicative of the pulse rate or oxygen saturation.

Amplification The signal received from the photodetector is typically weak and requires amplification. Using an operational amplifier configured with negative feedback helps enhance the signal strength without distorting its integrity, ensuring the accuracy of SpO2 calculations.

2.2.4 MOSFET and Zener Diode

- MOSFET: The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) in a pulse oximeter is used to control the current through the IR LED, thereby adjusting the light intensity based on the feedback received from the photodetector. This ensures consistent light transmission through various tissue densities.

- Zener Diode: This component creates a stable reference voltage in the circuit, known as the breakdown voltage. In pulse oximetry, the Zener diode is biased in its breakdown region to provide a stable voltage reference, which helps in setting the operating point of the amplifier and other signal conditioning circuits.

3 Design Specification

3.1 Overview

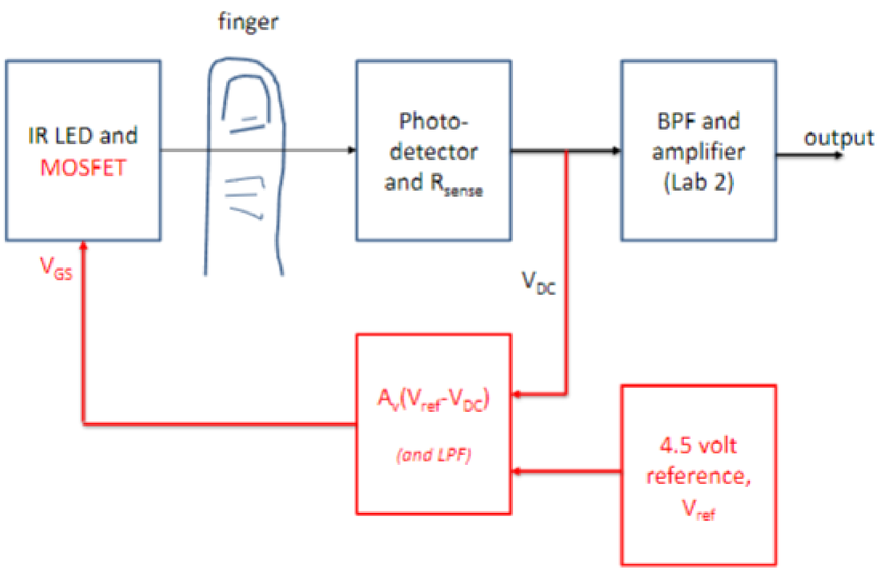

Fig 1. Block Diagram of Pulse Oximeter with Feedback Control

This block diagram represents a feedback control loop implemented in a pulse oximeter, designed to maintain a consistent light detection level. The system compensates for variations such as different finger thicknesses, which may alter the intensity of light reaching the photodetector.

- **IR LED and MOSFET**: The IR LED, driven by the MOSFET, emits infrared light that passes through the finger. The operation of the MOSFET, and thus the brightness of the LED, is controlled by the gate-source voltage V_{GS}.
- **Finger**: Acts as the medium through which the IR light passes. The finger's variable opacity, due to changing blood oxygen levels, affects the light transmission.
- **Photodetector and R_{sense}**: The photodetector, together with the sensing resistor R_{sense}, detects the transmitted light and converts it into a proportional electrical signal, resulting in a voltage V_{DC} that represents the detected light intensity.
- **BPF and Amplifier (Lab 2)**: Includes a band-pass filter (BPF) to isolate the pulsatile signal of interest and an amplifier to increase the signal's amplitude for further processing or display. This component is a carryover from a previous lab (Lab 2).
- **4.5-volt reference, V_{ref}**: A stable reference voltage provided by a Zener diode, crucial for setting the target level for V_{DC}.
- **Amplifier $A\ (V_{ref} - V_{DC})$ and LPF**: This amplifier, along with a low-pass filter (LPF), processes the difference between the reference voltage V_{ref} and the photodetector voltage V_{DC}, amplifying it to generate the control voltage

V_{GS} for the MOSFET. This forms the feedback loop that adjusts the IR LED's brightness to keep V_{DC} close to V_{ref}, thus stabilizing the sensor reading.

The feedback path is indicated by red lines in the diagram, highlighting the system's dynamic response to maintain a stable sensor output regardless of external changes such as finger placement or size.

3.2 BPF

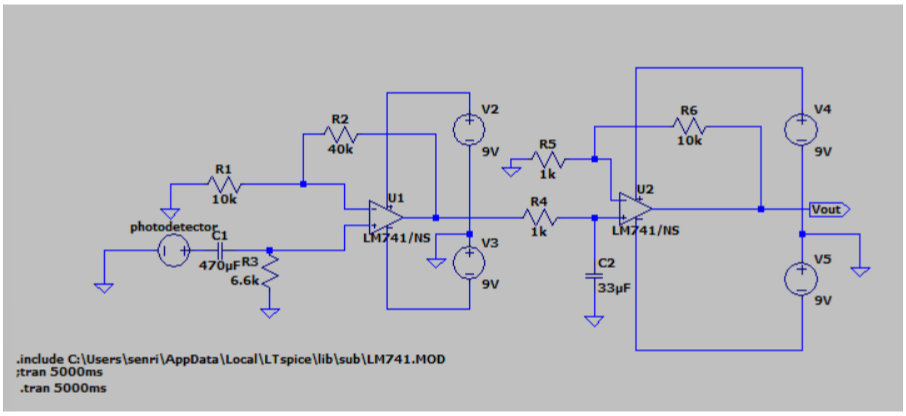

Fig. 2 LT Spice Schematics of Band Pass Filter impleted with High pass Filter and Low Pass Filter

Here's an outline of our circuit elements and their calculated parameters:

High-Pass Filter (HPF):

- **Resistors**:
  - $R1$: 10kΩ — sets the initial impedance of the HPF.
  - $R2$: 40kΩ — augments the gain of the HPF to a factor of 4.
  - $R3$: 6.6kΩ — complements the filtering action by shaping the frequency response.
- **Capacitor**:
  - $C1$: 470μF — selected based on availability and alignment with the calculated value from Lab 2 (330μF), ensuring the cutoff frequency targets the heart rate range.

Low-Pass Filter (LPF):

- **Resistors**:
  - $R4$: 1kΩ — achieves gain of 10 with R6.
  - $R5$: 1kΩ — maintains the integrity of the LPF.
  - $R6$: 10kΩ — achives gain of 10 with R4.
- **Capacitor**:

- $C2$: 33μF —chosen to complement R5 and R6, crafting a cutoff frequency that allows the desired signal while attenuating higher frequencies.

Power Supply and Load Resistor Considerations:

- $V1$: — Represents the input voltage received from the photodetector, which is powered by a steady 9V supply from V2, V3, V4, and V5.
- $LEDResistor$: 300Ω — calibrated to regulate the current through the IR LED, ensuring optimal illumination without risking overdrive.
- $SensingResistor$: 6.7kΩ — meticulously chosen to balance between voltage drop and sensitivity, enabling precise detection of blood oxygen saturation levels.

Transistor Operation and Voltage Calculations:

- The saturation voltage of the transistor is maintained at 0.4V to ensure it operates within its saturation region, which is critical for stable and efficient transistor performance. We derived an emittor resistor value of 10k to manage current flow, while Rsense was selected at 6.7k to optimize the phototransistor's operation for the anticiapted maximum current.

Filter Configuration and Total Gain:

- The combined high-pass and low-pass filters yield an aggregate gain of 55, crucial for enhancing the phototransistor's output signal to a discernible level for subsequent processing.

3.3 Difference Amplifier

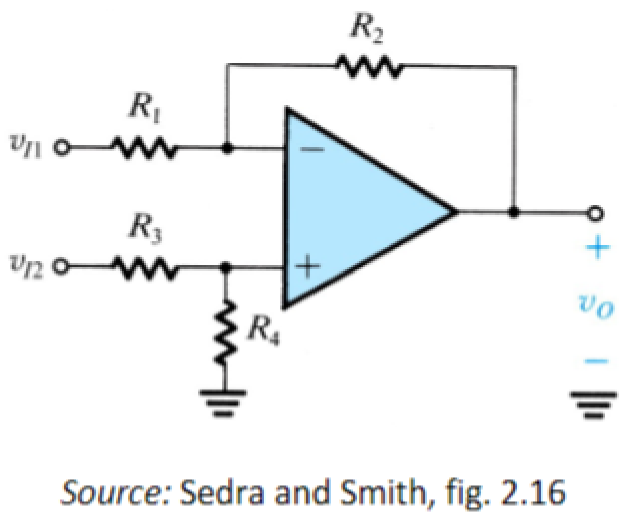

Fig. 3 Feedback Control using Difference Amplifier

The difference of VDC and VRef was amplified as a feedback control.
Components Values and Function:

- $R1\&R3$: 16kΩ
- $R2\&R4$: 160kΩ

- $Low\!-\!PassFilterCapacitance(Clpf)$:The Low-Pass Filter (LPF) capacitance, denoted as C_{lpf}, is selected to cut off frequencies higher than 0.1 Hz, which focuses on DC level adjustments and disregards the pulse frequency. This value is calculated using the formula for the cutoff frequency of a low-pass filter:

$$C_{\text{lpf}} = \frac{1}{2\pi R_2 f} = \frac{1}{2\pi \times 160,000 \times 0.1} \approx 10\mu F.$$

3.4 The Reference Source: Zener Diode

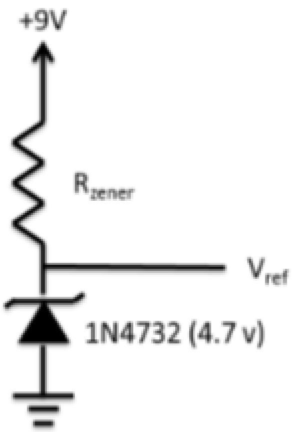

Fig. 4 Refence Voltage set by reverse biasing the zener diode

To establish a reliable reference voltage for the feedback system, a Zener diode (1N4732) with a breakdown voltage of 4.7V is utilized. The Zener diode is critical in maintaining a constant voltage regardless of variations in the load or input voltage fluctuations.

Zener Diode Specifications and Calculations:

- **Maximum Current Tolerance in Breakdown:** The Zener diode can tolerate up to 193 mA in breakdown.
- **Power Dissipation at Maximum Current:** Using the formula $P = IV$, where $I = 193\,\text{mA}$ and $V = 4.7\,\text{V}$, the power dissipation is calculated to be 907.1 mW.
- **Minimum Bias Resistor Calculation:** With a source voltage of 9 V, the smallest resistor that can be safely used is calculated by
$$\frac{V_{\text{source}} - V_z}{I_{zm}} = \frac{9 - 4.7}{0.193} = 22.28\,\Omega.$$
To ensure safety and reliability, a resistor 10 times this value, or 222.8 Ω, is used.
- **Power Dissipation in the Zener Diode Using Design Resistor:** The actual current through the Zener diode is
$$I = \frac{V_{\text{source}} - V_z}{R_{\text{safety}}} = \frac{9 - 4.7}{222.8} = 0.0193\,\text{A},$$

resulting in power dissipation of

$$P_{\text{zener}} = I \times V_z = 0.0193 \times 4.7 = 90.7\,\text{mW}.$$

3.5 MOSFET Current Control

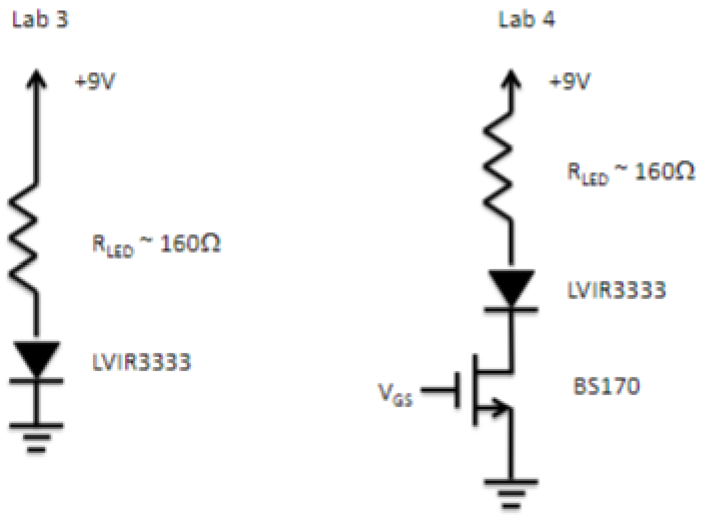

Fig. 5 MOSFET control of the current through the IR LED

The circuitry detailed above demonstrates the transition from the configuration used in Lab 3 to the enhanced design in Lab 4. In Lab 4, a MOSFET (BS170) is employed to regulate the current through an IR LED (LVR3333), which is essential for the operation of the pulse oximeter sensor.

Transistor Saturation and Voltage Calculations

- $V_{CE(sat)}$ (Collector-Emitter Saturation Voltage): 0.4V. This value is critical as it ensures the transistor is in the saturation region, where it operates most effectively for our application.
- Supply Voltage (V_{CC}): 9V.
- Voltage across the Emitter (V_E), Calculation of V_{sense}:
  - V_{sense} Calculation: $V_{sense} = V_{CC} - V_{CE(sat)} = 9V - 0.4V = 8.6V$. This voltage is the potential maximum value of V_{sense}, used for further calculations.
  - Emitter Resistor (R_E) Calculation:
    * $R_E = \frac{(V_{CC} - V_{CE(sat)})}{I_C} = \frac{8.6V}{1mA} = 8.6k\Omega$. This resistor sets the maximum current flow through the emitter when I_C (Collector Current) equals I_E (Emitter Current), assumed here as 1mA for calculation simplicity.
    * Chosen R_E adjusted to 10kΩ to ensure safe operation within device specifications.

4 Results

The functionality of the pulse oximeter was thoroughly tested under varied conditions to assess the effectiveness of the device.

4.1 Specification

The device tested for five different conditions.

- Person #1, light downward pressure on the finger
- Person #1, moderate pressure on the finger
- Person #2, light pressure
- Person #2, moderate pressure
- No finger in the pulse oximeter.

4.2 Person #1, Light Downward Pressure

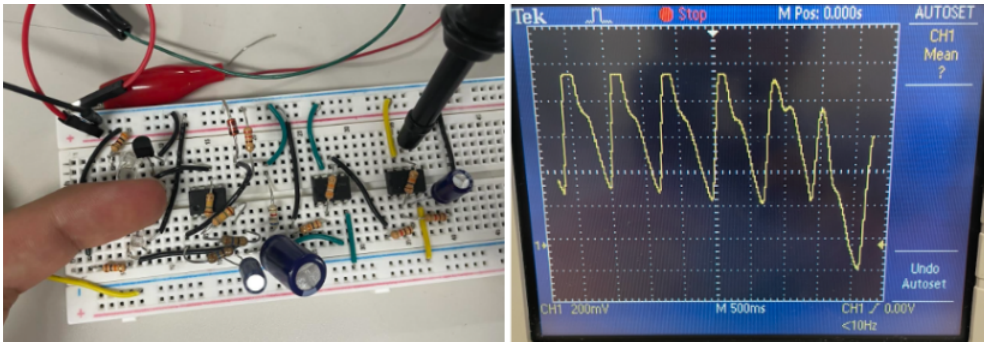

Fig. 6 Patient 1 applying light pressure

The device showed great responsiveness to small changes in pressure. The device is highly sensitive and precise.

4.3 Person #1, Moderate Downward Pressure

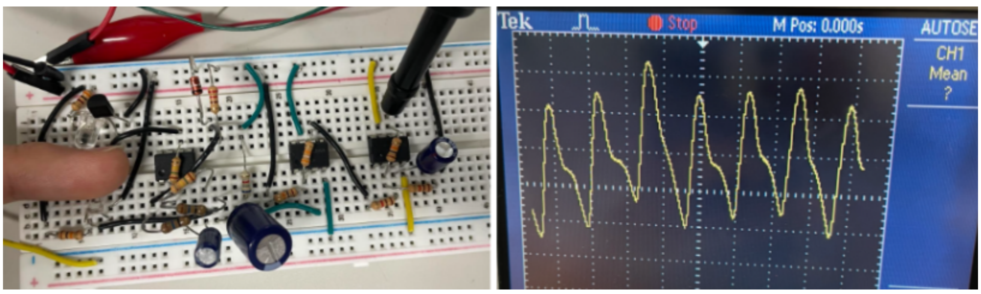

Fig. 7 Patient 1 applying moderate pressure

The system demonstrated maintaining accurate readings despite increased pressure, showcasing the feedback mechanism's ability to adapt dynamically.

4.4 Person #2, Light Downward Pressure

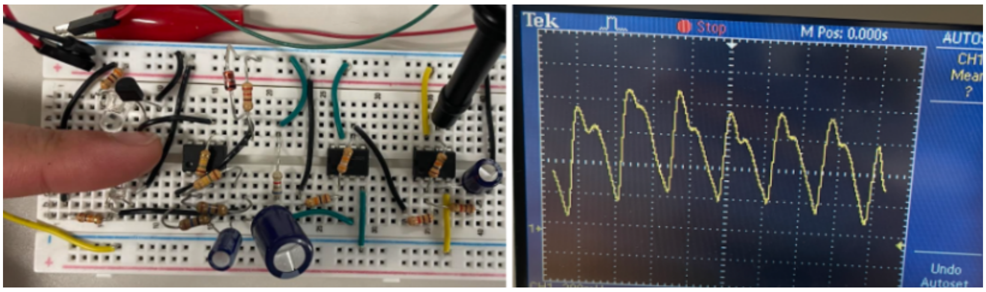

Fig. 8 Patient 2 applying light pressure

Similar tests with the patient 1 further confirmed the device's consistent performance across different users.

4.5 Person #2, Moderate Pressure

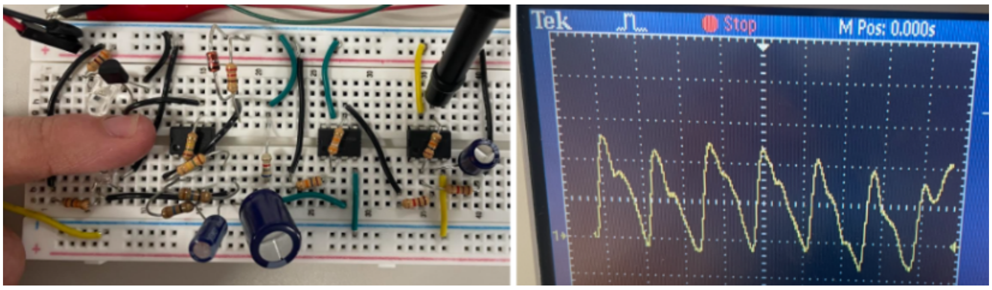

Fig. 9 Patient 2 applying moderate pressure

Again, the deviced showed excellence ability to maintain its output underpressure.

4.6 No finger in the pulse oximeter

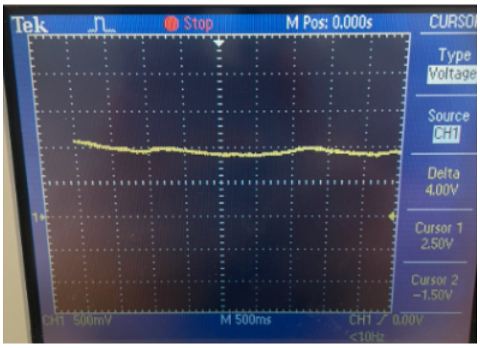

Fig. 10 No finger in the device

This control test confirmed zero output, validating the system's accuracy in null conditions and its ability to avoid false readings.

5 Ethical Considerations in Pulse Oximeter Design

5.1 Ethical Problems

- **Accuracy and Reliability:** There is an ethical imperative to ensure that the pulse oximeter provides accurate readings across diverse patient demographics, including varying skin pigmentation, which has been reported to affect the accuracy of some pulse oximeters.
- **Data Privacy and Security:** Modern pulse oximeters, especially those integrated into smart devices such as smartwatches, collect, store, and transmit health data, raising significant concerns regarding patient data privacy and protection from unauthorized access.

5.2 Affected Parties

- **Patients:** Depend on the accurate readings of pulse oximeters for critical health decisions. Inaccuracies can lead to misdiagnosis or improper treatment. Privacy breaches can impact personal data security.
- **Healthcare Providers:** Rely on the readings to make clinical decisions. Inaccurate readings can compromise the quality of care.
- **Manufacturers:** Responsible for device performance and compliance with privacy laws. Ethical lapses can result in legal consequences and reputation damage.

5.3 Sources for Learning About These Problems

- **Scientific Literature:** Peer-reviewed articles and studies on the performance of pulse oximeters across different populations.
- **Legal and Regulatory Documents:** HIPAA guidelines, FDA reports, and other regulatory documents set standards for patient data security and device accuracy.
- **Patents:** Provide information on the technologies used in pulse oximeters and safeguards for accuracy and privacy.

5.4 Ethical Guidelines Applicable to These Problems

- **Non-Discrimination:** The IEEE Code of Ethics mandates fairness and diversity consideration, crucial for ensuring device accuracy across all patient groups.
- **Safety and Welfare:** Engineers must prioritize the public's safety and health in their designs, including the reliability and accuracy of pulse oximeters.
- **Confidentiality:** The IEEE Code of Ethics and HIPAA stress the importance of maintaining the confidentiality of patient information.

5.5 Options and Suggested Responses

- **Improving Device Calibration and Testing:** Implement rigorous testing protocols that include a diverse sample population to ensure device accuracy.
- **Enhancing Data Encryption:** Apply advanced encryption methods for data transmission and storage to protect patient information.
- **Continuous Professional Development:** Engineers should remain updated on biomedical ethics and data security to maintain ethical standards and foster innovation.

6 Conclusion

The enhancement of pulse oximeters with dynamic feedback control represents a significant milestone in the field of biomedical engineering, improving the precision and dependability of devices used for patient monitoring. This initiative has successfully combined intricate systems capable of adjusting to the varied physiological attributes of patients, which is essential for accurate health assessments. The knowledge acquired from this project not only underscores the promise of technological progress but also the importance of maintaining ethical principles in the development and utilization of medical devices. Looking ahead, it is imperative to broaden clinical evaluations, refine the technology, and uphold ethical norms to propel healthcare technology towards more individualized and precise patient care methodologies.

An essential avenue for future research involves enhancing signal processing and refining the measurement of oxygen saturation. The forthcoming stage of development will delve into converting analog signals into digital information, with the aim of applying complex algorithms that yield more exact and steadfast oximetry readings. This progress seeks to fulfill the growing requirement for advanced processing systems capable of accurately interpreting oxygen saturation in a digital format.

Addressing variations in skin tone is just as important as the technological progression itself. Existing studies suggest potential variances in oximeter readings for individuals with darker skin tones. Moving forward, we plan to incorporate adaptable signal processing techniques that more effectively discern between the light absorption profiles of oxyhemoglobin and deoxyhemoglobin for patients of all backgrounds.