Non-Invasive Hemoglobin Monitoring Using Optical Sesnors

Dr.Arun.I
Assistant Professor
Department of Biomedical Engineering
J.N.N Institute of Engineering (Autonomous)
aruni@jnn.edu.in

Sivaranjani.T
Department of Biomedical Engineering
J.N.N Institute of Engineering (Autonomous)
sivaranjanit98@jnn.edu.in

Janani.A
Department of Biomedical Engineering
J.N.N Institute of Engineering (Autonomous)
janania85@jnn.edu.in

Bhargavi.S
Department of Biomedical Engineering
J.N.N Institute of Engineering (Autonomous)
bhargavis62@jnn.edu.in

Logeshwari.S
Department of Biomedical Engineering
J.N.N Institute of Engineering (Autonomous)
lokeswaris98@jnn.edu.in

ABSTRACT

Non-invasive hemoglobin monitoring through spectroscopy has emerged as a groundbreaking method in medical diagnostics, facilitating real-time, painless, and continuous evaluation of hemoglobin levels without the necessity for invasive blood draws. This approach primarily utilizes optical techniques, including Near-Infrared Spectroscopy (NIRS), Pulse CO-Oximetry, and the combination of optical and plethysmography sensors to measure hemoglobin concentration based on tissue absorption and scattering characteristics. These techniques offer significant benefits in clinical environments, especially for patients who require regular monitoring, such as those suffering from anemia, chronic kidney disease, or those undergoing surgical procedures. This paper examines the underlying principles, technologies, clinical applications, and future potential of non-invasive hemoglobin monitoring through spectroscopy.

Keywords: Non-invasive hemoglobin monitoring, optical sensors, real-time monitoring, anemia, medical diagnostics.

1. INTRODUCTION

1.1 Overview

Hemoglobin is a critical protein in red blood cells responsible for oxygen transportation throughout the body. Monitoring hemoglobin levels is essential in diagnosing and managing various medical conditions, such as anemia, chronic kidney disease, cardiovascular disorders, and post-surgical recovery. Traditional hemoglobin testing methods, such as Complete Blood Count (CBC) tests and point-of-care (PoC) hemoglobin meters, require invasive blood sampling, which can be painful, time-consuming, and prone to infection risks. Additionally, these methods require laboratory analysis, which may delay diagnosis and increase healthcare costs.To overcome these challenges, Non-Invasive Hemoglobin Monitoring Using Spectroscopy offers a revolutionary approach. This project focuses on designing a non-invasive, real-time hemoglobin monitoring system using Near-Infrared Spectroscopy (NIRS), Pulse CO-Oximetry, and Photoplethysmography (PPG) sensors. These optical techniques work by analyzing light absorption and scattering properties in human tissues to estimate hemoglobin concentration without the need for blood samples.

The proposed system integrates:

Multi-wavelength light absorption techniques to accurately measure hemoglobin levels. Advanced signal processing to filter out motion artifacts and noise. IoT-based cloud integration for real-time remote monitoring of hemoglobin levels.

This technology can be miniaturized into wearable devices, allowing for continuous, painless, and real-time hemoglobin monitoring, significantly improving patient care in clinical, home-based, and remote healthcare settings.

1.2 Purpose of the Project

The purpose of this project is to develop a portable, non-invasive hemoglobin monitoring system that provides accurate, real-time, and painless measurements of haemoglobin levels.

Key Objectives:

1.2.1 Eliminate the need for invasive blood sampling:

Reduces discomfort, especially for patients requiring frequent monitoring. Prevents needle-related complications such as hematomas and infections.

1.2.2 Enable continuous and real-time monitoring:

Useful in critical care, emergency settings, and surgical procedures where immediate hemoglobin readings are necessary.Provides trend analysis to detect early signs of anemia or blood loss.

1.2.3 Enhance accessibility and usability in resource-limited areas:

Reduces dependence on laboratory-based testing. Supports rural healthcare and mobile medical units where laboratory access is limited.

1.2.4 Improve accuracy through sensor technology and machine learning:

Advanced optical sensors ensure precise readings. Machine learning models correct inaccuracies caused by skin pigmentation, motion artifacts, and environmental factors.

The target audience for this project includes:

Patients with anaemia, kidney disease, or blood disorders requiring regular monitoring. Neonates, pregnant women, and elderly individuals where blood draws can be challenging. Athletes and fitness enthusiasts who want to track their oxygen-carrying capacity. Healthcare providers in emergency care, ICUs, and operation theaters for quick decision-making. By achieving these objectives, this project aims to revolutionize hemoglobin monitoring, making it more patient-friendly, efficient widely accessible.

1.3 Motivation

The motivation behind this project stems from critical challenges in traditional haemoglobin testing and the increasing demand for advanced healthcare solutions.

1.3.1 Challenges in Traditional Haemoglobin Monitoring

Conventional blood tests involve venous or capillary blood draws, causing pain, discomfort, and anxiety, especially for children and elderly patients. Blood sampling poses infection risks, particularly in immune compromised patients. Frequent blood draws can cause complications like bruising, hematomas, or vein collapse. Conventional tests require sample collection, transportation, and lab processing, leading to delays in diagnosis and treatment. In emergency settings, such delays can be life-threatening. Many remote regions lack proper laboratory infrastructure. Patients often have to travel long distances for simple blood tests, making healthcare inaccessible. Patients often avoid frequent testing due to needle phobia, inconvenience, or cost concerns.

1.3.2 The Need for Non-Invasive Hemoglobin Monitoring

To address these challenges, non-invasive hemoglobin monitoring presents an innovative solution that is:

Eliminates the need for needles, reducing patient anxiety and improving compliance. Provides instant readings, allowing for early diagnosis and timely interventions. Can be used in rural health centres, mobile clinics, and home-based monitoring. Portable design makes it suitable for military, space missions, and disaster response. Reduces the need for repeated lab visits and expensive diagnostic tests. Beneficial for low-income populations and healthcare systems in developing countries. Can be embedded in smart watches, fitness bands, and IoT health monitoring systems. Enables remote monitoring, supporting the future of digital healthcare and telemedicine.

1.3.3 Impact of the Project

By developing a non-invasive hemoglobin monitoring system, this project has the potential to:

Improve patient experience by making hemoglobin testing painless and hassle-free. Enhance healthcare accessibility for people in remote and underserved

VOLUME: 09 ISSUE: 04 | APRIL - 2025 SJIF RATING: 8.586 ISSN: 2582-3930

areas. Reduce diagnostic delays, leading to better management of anemia, kidney diseases, and surgical recovery. Promote preventive healthcare, encouraging regular hemoglobin monitoring to detect issues before they become critical. Integrate with advanced AI and IoT-based health monitoring systems, paving the way for next-generation smart healthcare devices.

1. LITERATURE SURVEY

The field of non-invasive hemoglobin monitoring has evolved significantly over the years, driven by advancements in optical spectroscopy, photoplethys mography (PPG), and machine learning-based health monitoring. Several research studies and technological developments have contributed to this innovation.

2.1 Key Research and Studies

2.1.1. Near-Infrared Spectroscopy (NIRS) for Hemoglobin Estimation

Researchers have explored the use of Near-Infrared Spectroscopy (NIRS), which utilizes light absorption properties of hemoglobin at different wavelengths.

Findings: Studies indicate that NIRS can differentiate oxygenated and deoxygenated hemoglobin, making it suitable for real-time, non-invasive monitoring.

Challenges: However, skin pigmentation, tissue thickness, and motion artifacts can affect accuracy, requiring advanced signal processing.

2.1.2. Photoplethysmography (PPG) in Hemoglobin Monitoring

PPG-based techniques have been extensively studied for monitoring blood volume changes using light absorption. Research has demonstrated that PPG signals collected from the fingertip or earlobe can provide indirect hemoglobin measurements. Integration with AI algorithms has further improved reliability by compensating for noise and variations.

2.1.3. Wearable Non-Invasive Hemoglobin Monitors

Companies and research groups are developing wearable devices capable of tracking hemoglobin levels continuously.

Example: Some smartwatches and fitness trackers now feature PPG and SpO2 sensors, which could be adapted for hemoglobin monitoring.

2.1.4 Gaps in Existing Research

Despite significant advancements, non-invasive hemoglobin monitoring is not yet widely adopted due to the following limitations:

Accuracy Issues: Variations due to motion artifacts, skin tone differences, and environmental factors can affect readings.

Standardization Challenges: No universally accepted standard exists for non-invasive hemoglobin measurement techniques.

Integration with Healthcare Systems: Many non-invasive methods are still in the research phase and need clinical validation before large-scale implementation.

This project aims to bridge these gaps by integrating advanced optical sensors, machine learning algorithms, and IoT connectivity, making non-invasive hemoglobin monitoring more practical and widely accessible.

2.2 Existing System

Currently, hemoglobin monitoring is primarily performed using invasive blood tests, requiring venous or capillary blood samples for laboratory analysis. The most commonly used methods include:

2.2.1 Complete Blood Count (CBC) Test

Process:

Blood is drawn from a vein using a syringe and sent to a laboratory. The hemoglobin concentration is measured using automated hematology analyzers.

Limitations:

Invasive and painful process requiring needle pricks. Time-consuming, as samples must be processed in a lab. Risk of infections due to repeated blood draws. Not feasible for continuous real-time monitoring.

2.2.2 Point-of-Care (PoC) Hemoglobin Meters

Process:

Requires a small blood sample (finger prick) placed on a testing strip. A handheld PoC device provides quick hemoglobin readings.

Limitations:

Still requires a blood sample, making it minimally invasive. Not suitable for continuous monitoring, as each test requires a new blood drop. Accuracy may be affected by improper sample collection or device calibration issues.

2.2.3 Pulse Oximetry (SpO2 Sensors in Smart Devices)

Process:

Measures oxygen saturation (SpO2) in the blood by passing light through the skin (usually a fingertip or wrist).

Limitations:

Does not measure hemoglobin directly; it only provides an estimate of oxygen levels. Not reliable for diagnosing anemia or blood disorders.

2.2.4 Laboratory-Based Hemoglobin Electrophoresis

Process:

A specialized blood test that separates different types of hemoglobin for diagnosis of genetic blood disorders.

Limitations:

Requires large blood samples and specialized laboratory equipment.

Expensive and time-consuming, making it impractical for routine monitoring.

2.3 Limitations of the Existing System

Despite being widely used, traditional hemoglobin monitoring systems have several drawbacks that highlight the need for a non-invasive alternative.

2.3.1 Invasiveness and Patient Discomfort

Blood sampling involves needle pricks, which can be painful, anxiety-inducing, and inconvenient for patients. Patients requiring frequent testing (e.g., anemic, dialysis, or ICU patients) must undergo repeated blood draws, leading to vein damage and discomfort.

2.3.2 Infection Risks

Invasive methods pose a risk of infections, especially in immunocompromised individuals, newborns, and elderly patients. Improper sterilization of needles can lead to bloodborne infections.

2.3.3 Delays in Diagnosis and Treatment

Lab-based methods require time for sample collection, transportation, and analysis, delaying immediate decision-making in emergency cases. Remote areas with limited lab access may suffer from long turnaround times, making early diagnosis difficult.

2.3.4 High Costs and Resource Requirements

Traditional blood tests require laboratory facilities, trained personnel, and consumables (needles, syringes, reagents, etc.), increasing healthcare costs. In resource-limited settings, access to hemoglobin testing is restricted due to financial and logistical barriers.

2.3.5 Lack of Continuous Monitoring

Current systems provide only one-time readings, requiring multiple blood draws for tracking hemoglobin levels over time. Non-invasive, real-time monitoring is needed for better patient management, especially in ICU, neonatal care, and home-based health monitoring.

2.3.6 Variability in Test Results

Hemoglobin readings can vary due to hydration levels, sample handling, and different laboratory equipment calibration.

Point-of-care devices may show inconsistencies due to external factors such as temperature, altitude, or improper finger prick techniques.

PROPOSED SYSTEM

3.1 Proposed System

The proposed system aims to develop a non-invasive hemoglobin monitoring device using spectroscopy-based optical sensors. Instead of traditional invasive methods that require blood samples, this system uses light absorption and scattering properties to estimate hemoglobin concentration in real time.

Key Features of the Proposed System:

Non-invasive measurement: No need for blood samples, making it painless and comfortable for patients.

Real-time monitoring: Provides instant hemoglobin readings through Serial Monitor and ThingSpeak IoT platform.

Portable and cost-effective: Compact design suitable for home, clinical, and remote healthcare applications.

Easy to use: No specialized training required for operation, making it accessible to all users.

This system is particularly beneficial for:

Patients with anemia, kidney diseases, and chronic illnesses requiring frequent hemoglobin monitoring.

Emergency and surgical cases, where instant hemoglobin readings are crucial.

Rural and underdeveloped areas with limited access to laboratory-based testing.

3.2 Objectives of the Proposed System

Primary Objectives:

Develop a non-invasive method for hemoglobin measurement using spectroscopy and optical sensors.

Make the system cost-effective and portable, enabling use in resource-limited areas. Enhance accuracy and reliability by filtering out motion artifacts and external light interference.

Secondary Objectives:

Provide a simple and user-friendly interface using Arduino/ESP32-based microcontroller.

Optimize power consumption, making the system suitable for wearable or portable healthcare devices.

Enable cloud-based remote monitoring by integrating the system with ThingSpeak IoT analytics.

3.3 SYSTEM REQUIREMENTS

3.3.1 Software Requirements

The system software is responsible for:

Software Components:

Arduino IDE – Used for writing and uploading the microcontroller code.

ESP32/Arduino libraries – Required for interfacing with sensors and ThingSpeak.

3.3.2 Hardware Requirements

The hardware components include:

Core Components:

Arduino/ESP32 Microcontroller – Handles sensor data processing and transmission.

Near-Infrared Spectroscopy (NIRS) Sensor – Measures hemoglobin concentration using light absorption.

Pulse CO-Oximetry Sensor – Provides additional hemoglobin-related data.

Photoplethysmography (PPG) Sensor – Captures blood volume changes to estimate hemoglobin levels.

Indicators – For status alerts (optional, as display is via Serial Monitor and ThingSpeak).

Supporting Components:

Resistors, capacitors, and connecting wires – For circuit stability. USB Cable – For programming and power supply. Power Supply (Battery/USB Adapter) – To run the system.

3.3.3 Functional Requirements

The proposed system must perform the following functions:

Data Collection: Sensors collect real-time hemoglobin-related data.

Data Processing: The microcontroller filters noise and converts raw data into meaningful readings.

Data Transmission: Processed data is:

Displayed on Serial Monitor for real-time debugging. User Alerts (Optional): Can trigger visual or buzzer alerts for abnormal hemoglobin levels.

3.3.4 Non-Functional Requirements

Accuracy & Reliability: The system must provide consistent and precise readings despite external factors. Low Power Consumption: The device should be optimized for battery-powered operation. Portability: The system should be lightweight and compact for easy

INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH IN ENGINEERING AND MANAGEMENT (IJSREM)
VOLUME: 09 ISSUE: 04 | APRIL - 2025 SJIF RATING: 8.586 ISSN: 2582-3930

handling. Cloud Integration: The system should seamlessly upload data to ThingSpeak for continuous monitoring. Data Security: Ensure secure data transmission via Wi-Fi or Bluetooth (for ESP32-based systems).

3.4 CONCEPTS USED IN THE PROPOSED SYSTEM

3.4.1. Optical Spectroscopy for Hemoglobin Measurement

Concept: Hemoglobin absorbs light at specific wavelengths. By measuring light absorption through tissue, hemoglobin levels can be estimated. Sensors Used: Near-Infrared Spectroscopy (NIRS) and Pulse CO-Oximetry.

3.4.2. Photoplethysmography (PPG) for Blood Volume Analysis

Concept: Light from a PPG sensor reflects changes in blood volume, which correlates with hemoglobin concentration. Implementation: Data is processed through the microcontroller to estimate hemoglobin levels.

3.5 DATA SET USED IN THE PROPOSED SYSTEM

The system does not use a predefined dataset, as it collects real-time data from sensors. However, it requires initial calibration using sample test data to improve accuracy.

3.5.1 Calibration Process:

Baseline Readings:

Initial hemoglobin levels are measured using standard laboratory tests. These values are used to calibrate the sensor output.

Real-Time Sensor Data Collection:

The system records multiple readings under different conditions (e.g., different skin tones, lighting conditions). Data is stored for analysis and adjustment.

Sensor Tuning:

Adjustments are made to improve accuracy, ensuring sensor readings closely match gold-standard hemoglobin tests.

4. SYSTEM DESGIN

4.1.1 Hardware Components

4.1.1.1 Optical Sensors for Hemoglobin Measurement

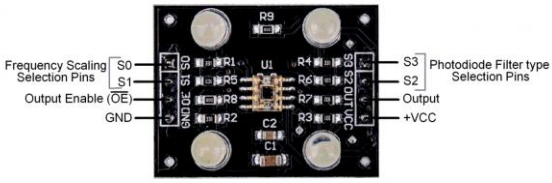

Figure. No. (1) TCS3200 OPTICAL SESNOR

At the heart of this system are optical sensors, which function using the principles of light absorption and scattering. Hemoglobin, the oxygen-carrying protein in red blood cells, has unique absorption characteristics at different wavelengths of light. By measuring how much light is absorbed and transmitted, the system can estimate hemoglobin concentration without drawing blood.

Near-Infrared Spectroscopy (NIRS) Sensor

Figure. No. (2) Near-Infrared Spectroscopy (NIRS) sensor MAX320100

The Near-Infrared Spectroscopy (NIRS) sensor plays a crucial role in hemoglobin measurement. This sensor works by emitting near-infrared light (650–1000 nm) onto the skin and detecting how much of that light is absorbed by hemoglobin molecules. Since oxygenated and deoxygenated hemoglobin absorb light differently, analyzing these absorption patterns allows the system to determine hemoglobin levels in real time.

The NIRS sensor is typically placed on a fingertip or earlobe, where capillary blood flow is strong and external interference is minimal. A photodetector on the other side of the sensor captures the light that passes through the tissue, and the microcontroller processes this data to estimate hemoglobin concentration.

Pulse CO-Oximetry Sensor

The Pulse CO-Oximetry sensor extends the functionality of NIRS by using multiple wavelengths of light to differentiate between various forms of hemoglobin:

Oxygenated Hemoglobin (HbO2) – Carries oxygen. Deoxygenated Hemoglobin (HHb) – Oxygen-depleted hemoglobin

Figure. No. (3) HRE2500 PLUSE SESNOR

By measuring the ratio of HbO2 to HHb, the sensor can provide an even more precise estimation of total hemoglobin concentration and oxygen saturation levels. This feature is essential for monitoring patients with anemia, chronic diseases, or those recovering from surgery.

Photoplethysmography (PPG) Sensor

The Photoplethysmography (PPG) sensor measures blood volume changes using light absorption. Since blood volume fluctuates with each heartbeat, the sensor detects how blood flow modulates light absorption over time. This real-time data helps in continuous hemoglobin monitoring, making PPG sensors particularly useful in wearable health devices.

The PPG sensor emits red or infrared light, and the photodetector captures the reflected light to analyze blood volume variations. These readings are processed by the microcontroller to estimate circulating hemoglobin levels dynamically.

4.1.1.2 Microcontroller (Arduino/ESP32)

Arduino is an open-source electronics platform based on easy-to-use hardware and software. It consists of a microcontroller (usually an AT Mega series chip) that can be programmed to perform various tasks. The platform provides a simple way for beginners and enthusiasts to create interactive electronic projects without in-depth knowledge of electronics or programming.

Here's a breakdown of how Arduino works:

Hardware: Arduino boards are the physical component of the platform. They contain a microcontroller, which is the brain of the system. Arduino boards come in different shapes and sizes, each designed for specific purposes. They have input and output pins that can be used to connect various components like sensors, actuators, and other peripherals.

Programming: Arduino programming is done using the Arduino Integrated Development Environment (IDE). This IDE is a software application that allows you to write, compile, and upload code to the Arduino board. The code is written in a simplified version of C/C++ programming language. The IDE provides built-in functions and libraries that simplify tasks like reading sensor data, controlling outputs, and communicating with other devices.

Figure. No. (5) Real Time Arduino

Sketches: In Arduino, programs are referred to as "sketches." A sketch is a set of instructions that the microcontroller follows. It typically consists of two essential functions: `setup()` and `loop()`. The `setup()` function is executed once at the beginning of the program, and the `loop()` function runs repeatedly after the `setup()` is completed.

VOLUME: 09 ISSUE: 04 | APRIL - 2025 SJIF RATING: 8.586 ISSN: 2582-3930

Interfacing: Arduino can interface with various electronic components such as sensors (temperature, light, distance, etc.), actuators (motors, LEDs, etc.), displays, and communication modules (Bluetooth, Wi-Fi, etc.). These components are connected to the input/output pins of the Arduino board. By writing code, you can control these components and respond to the data they generate.

Input and Output: Arduino reads data from sensors connected to its input pins and processes this data using the programmed instructions. It can then make decisions and control outputs (such as turning on a motor or an LED) using its output pins. For instance, you can program it to light up an LED when a certain condition is met or to move a servo motor based on sensor readings.

Upload : Once the code (sketch) is written in the Arduino IDE, you can upload it to the Arduino board. The IDE compiles the code into machine-readable instructions that the microcontroller can understand. These instructions are then loaded onto the microcontroller's memory, allowing it to execute the programmed tasks.

Execution: After the code is uploaded, the microcontroller follows the instructions in the `setup()` function once, initializing variables and settings. Then, it enters the `loop()` function, where it repeats the programmed tasks indefinitely until power is disconnected or the code is modified and re-uploaded.

In essence, Arduino simplifies the process of creating electronic projects by providing an approachable programming environment and a hardware platform that can interact with a wide range of components. It's widely used in hobbyist projects, educational settings, and even in some professional applications due to its flexibility and ease of use.

ESPESP32

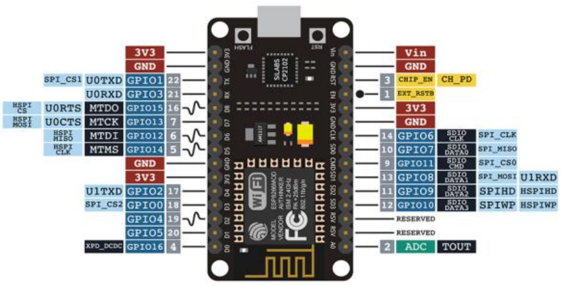

Figure. No. (6) ESP8266/ESP 32

ESP32:

Dual-Core Processor: Dual-core Tensilica LX6 microprocessors.

Wireless Connectivity: Wi-Fi and Bluetooth connectivity (BLE) in a single module.

More GPIO Pins: Higher number of GPIO pins compared to ESP8266.

Peripheral Interfaces: Support for a wide range of interfaces, including SPI, I2C, UART, and more.

Bluetooth Capabilities: Integrated Bluetooth Low Energy (BLE) for communication with other devices.

Enhanced Features: Supports more advanced features like touch sensors, ADCs, and DACs.

4.1.1.3 Power Supply

The system requires a stable power source for continuous operation. It can be powered by:

USB Connection: Ideal for stationary setups such as hospital monitoring systems. Rechargeable Battery: Suitable for portable and wearable applications, ensuring flexibility in use.

4.1.1.4 Data Transmission and Display

After processing, the hemoglobin readings are displayed and transmitted for analysis. The system supports two display modes:

Real-time display on Serial Monitor (PC/Laptop): The microcontroller outputs hemoglobin levels for instant debugging and analysis.

4.1.2 Software Components

4.1.2.1 Arduino IDE for Programming

The Arduino IDE is used to program the microcontroller. It includes:

Code for sensor data acquisition and processing. Libraries for handling NIRS, PPG, and Pulse CO-Oximetry sensors.

4.2 Proposed System Architecture

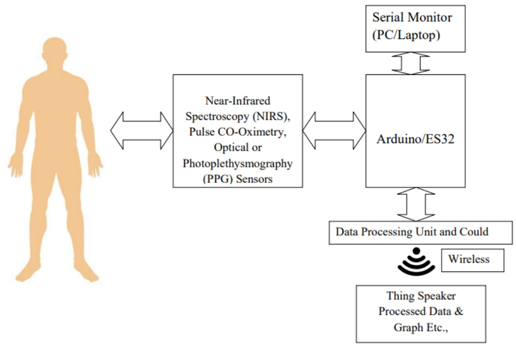

Figure. No. (8) Block Diagram

The proposed system architecture defines the flow of data from sensor detection to final visualization. The architecture ensures accurate, real-time, and non-invasive hemoglobin monitoring while maintaining low power consumption and portability. The system is designed in a layered approach, consisting of:

Data Collection Layer: Where optical sensors capture light absorption variations.

Data Processing Layer: Where the microcontroller filters noise and estimates hemoglobin levels.

Data Transmission Layer: Where the processed hemoglobin readings are displayed on the Serial Monitor and optionally uploaded to ThingSpeak (if using ESP32 for IoT integration).

Each layer performs specific tasks that contribute to the overall efficiency of the system. Below, we examine the workflow and communication flow in detail.

4.2.1 System Workflow

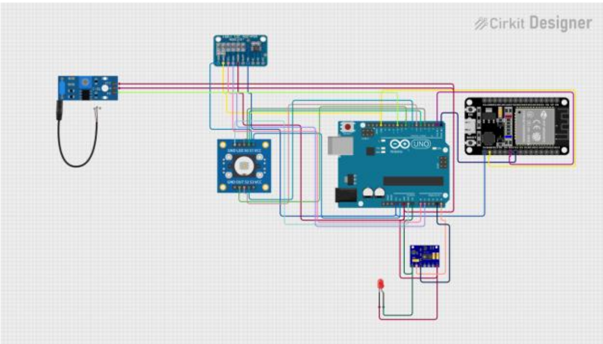

Figure. No. (9) Circuit Diagram

The workflow of the system describes how hemoglobin data is collected, processed, and transmitted in real time. The process consists of three primary stages:

Step 1: Data Collection (Sensor Layer)

The first step in the system involves data collection using optical sensors, which detect hemoglobin levels based on light absorption principles. The sensors are placed on a fingertip or earlobe, where blood circulation is strong and external interference is minimal.

Near-Infrared Spectroscopy (NIRS) Sensor: Emits near-infrared (NIR) light onto the skin, measuring how much light is absorbed by hemoglobin molecules.

Pulse CO-Oximetry Sensor: Uses multiple wavelengths of light to differentiate oxygenated and deoxygenated hemoglobin, improving accuracy.

Photoplethysmography (PPG) Sensor: Monitors blood volume fluctuations, which correlate with hemoglobin concentration. *How Light Absorption Works in the System*

The optical sensors emit light onto the skin.

Some light is absorbed by hemoglobin, while the rest is transmitted or scattered.

A photodetector captures the transmitted light, which varies depending on hemoglobin concentration in the blood.

The captured signal is converted into an electrical signal and sent to the microcontroller for processing.

Since different hemoglobin levels result in varying absorption patterns, the system can estimate hemoglobin concentration without requiring a blood sample.

Step 2: Data Processing (Microcontroller Layer)

After data collection, the raw signals from the sensors are sent to the Arduino/ESP32 microcontroller, which is responsible for processing and filtering the data. The raw sensor data is often affected by motion artifacts, skin pigmentation, and external lighting conditions, so the microcontroller applies signal filtering techniques to improve accuracy.

How the Microcontroller Processes the Data:

Analog-to-Digital Conversion (ADC): Since sensors generate analog signals, the microcontroller first converts them into digital form for processing.

Noise Filtering: The system applies signal processing algorithms to eliminate interference caused by movement, skin tone variations, and ambient light.

Calibration: The system compares the processed data with standard hemoglobin readings to ensure accuracy.

Hemoglobin Level Estimation: The final processed value is then calculated based on the absorption characteristics of hemoglobin at different wavelengths.

To further improve measurement precision, the system periodically recalibrates itself by adjusting sensor readings based on predefined calibration parameters.

Once the hemoglobin levels are estimated, they are formatted for display and transmission.

Step 3: Data Transmission (Display & IoT Integration Layer)

Once the hemoglobin levels are processed, they are displayed in real time for immediate use. The system offers two output options:

Serial Monitor (PC/Laptop) Display

The microcontroller sends hemoglobin readings to the Serial Monitor, where they are displayed as real-time numerical values. The Serial Monitor is useful for immediate visualization and debugging during system development. If necessary, the data can be logged and analyzed further for trend analysis.

4.2.2 Communication Flow

The communication flow describes how different components interact within the system. The process follows a structured pipeline, ensuring seamless data transfer from sensors to final visualization.

4.2.2.1 Sensors → Microcontroller: Capturing Light Absorption Data

The process starts with optical sensors placed on the user's fingertip or earlobe. These sensors emit specific wavelengths of light, and the photodetector measures how much light is absorbed by hemoglobin molecules. The raw data from the sensors is in analog form, so it must be converted into a digital format before further processing.

Once captured, the sensor signals are sent to the Arduino/ESP32 microcontroller for processing. However, this raw data is often noisy due to motion artifacts, variations in tissue thickness, and environmental light interference.

4.2.2.2 Microcontroller Processing: Signal Filtering and Hemoglobin Estimation

Upon receiving the raw sensor data, the Arduino/ESP32 microcontroller performs several important tasks to ensure the accuracy and reliability of the hemoglobin readings:

Analog-to-Digital Conversion (ADC):

Since the sensor output is analog, it is first converted into digital form by the microcontroller.

Noise Filtering and Artifact Removal:

Motion artifacts (caused by finger movement) and environmental noise (caused by ambient light) are filtered using digital signal processing (DSP) techniques.

Data Calibration:

The system compares real-time readings with stored reference values to improve accuracy.

Hemoglobin Calculation:

Using predefined calibration formulas, the microcontroller estimates hemoglobin concentration based on light absorption characteristics.

Once processed, the final hemoglobin value is ready for display.

4.2.2.3. Data Display: Visualization on Serial Monitor and ThingSpeak Cloud

After processing, the hemoglobin readings are transmitted for final display. The system supports two output methods:

Display on Serial Monitor

The processed hemoglobin levels are sent to the Serial Monitor (PC/Laptop) for real-time visualization.

This allows for immediate analysis and is useful for system debugging.

Upload to ThingSpeak (IoT Integration – If ESP32 is Used)

If the ESP32 microcontroller is used, the hemoglobin readings are sent to ThingSpeak via Wi-Fi.

Users can remotely access their hemoglobin data from anywhere through a ThingSpeak dashboard.

The data is displayed in graphical charts, allowing users to track long-term trends and fluctuations.

RESULTS

5.1 Serial Monitor output

The Serial Monitor output (as seen in the second image) displays three key physiological parameters:

Pulse Rate (BPM): Indicates the number of heartbeats per minute. The readings show a stable 75 BPM, meaning the sensor is accurately detecting the pulse.

Red Wavelength Readings: The sensor captures the intensity of light absorption at a specific red wavelength. The variations in this value help determine hemoglobin concentration in the blood.Hemoglobin Levels: The estimated hemoglobin concentration is derived from the light absorption values.

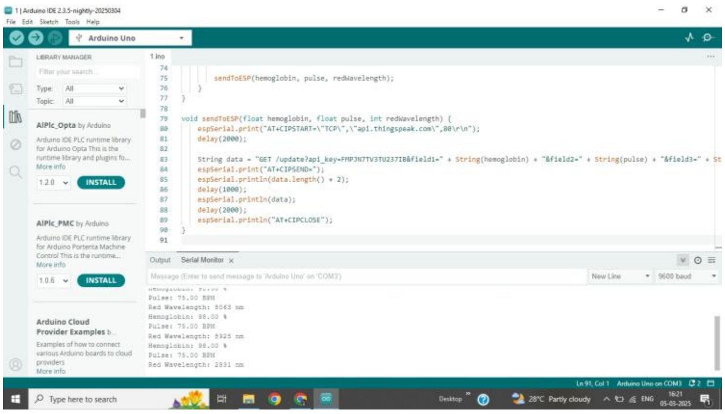

Figure. No. (10) Serial Monitor Output

The Arduino code snippet in the image highlights how these values are captured and processed before being transmitted to ThingSpeak. The function sendToESP() prepares the data for IoT transmission.

5.2. IoT-Based Data Transmission and Visualization

5.2.1 Data Upload to ThingSpeak

The system uses an ESP8266 or ESP32 module to send the captured data to ThingSpeak, a cloud-based IoT platform.

The Arduino code executes AT commands to establish a TCP connection with the ThingSpeak API, allowing data to be uploaded in real time.

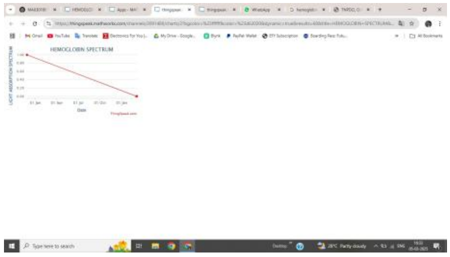

Figure. No. (11) Output 1

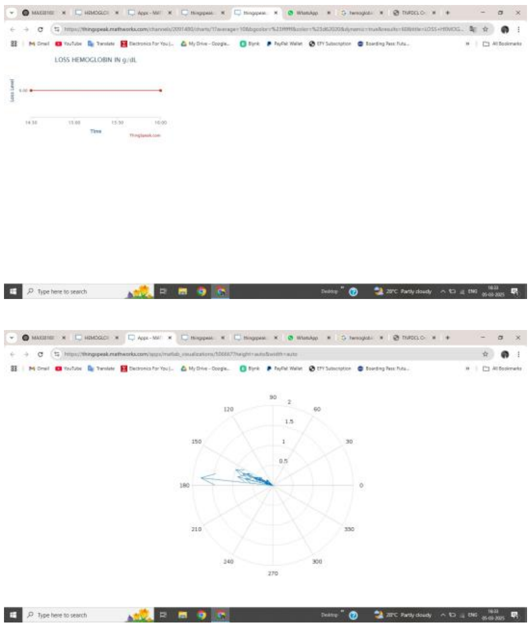

Figure. No. (12) Output 2

6.2.2 Visualization in ThingSpeak

The graph in the first image plots light absorption (Y-axis) against time (X-axis) under the title "Hemoglobin Spectrum."

The data shows a declining trend, meaning that the measured light absorption levels are decreasing over time, which could indicate:

A drop in hemoglobin concentration, if the subject's hemoglobin levels are genuinely reducing.

Sensor inaccuracies or calibration issues, which may require further adjustments.

Environmental or placement factors, like finger pressure on the sensor, ambient light interference, or movement artifacts.

Comparison of Traditional and Non-Invasive Hemoglobin Measurement Methods

Feature	Traditional Method (Invasive Blood Test)	Non-Invasive Method (Optical Monitoring)
Procedure	Blood sample drawn via needle	Uses optical sensors to measure hemoglobin levels through skin/tissue
Pain & Discomfort	Painful due to needle insertion	Painless and comfortable for the patient
Risk of Infection	Risk of infection and contamination	No risk of infection, as there is no skin penetration
Real-Time Monitoring	No, requires lab processing	Yes, provides continuous or instant results
Measurement Time	Minutes to hours (lab-dependent)	Instant or within seconds
Portability	Requires clinical setup and trained personnel	Compact, wearable, and portable devices available
Cost	Higher due to lab processing and consumables	Lower operational cost after initial device investment
Patient Suitability	Limited for critically ill or needle-averse patients	Suitable for all, including infants, elderly, and critically ill patients
Accuracy & Calibration	High accuracy, but dependent on lab errors	Accuracy depends on calibration and algorithm optimization
Use Case	Routine check-ups, hospital-based diagnostics	Home monitoring, emergency care, and continuous patient assessment

CONCLUSION

The non-invasive hemoglobin monitoring system offers a painless, real-time, and cost-effective alternative to traditional blood tests by utilizing optical spectroscopy, microcontroller-based processing, and IoT-enabled remote monitoring. Unlike invasive methods, this system estimates hemoglobin levels using light absorption principles, displaying real-time readings on a Serial Monitor and enabling remote tracking via ThingSpeak (if ESP32 is used). Its portability makes it ideal for home use, hospitals, and rural healthcare, reducing costs, discomfort, and dependency on laboratory testing.

This system enhances preventive healthcare by allowing continuous hemoglobin monitoring, particularly benefiting individuals with anemia, kidney disease, and chronic conditions. While challenges like sensor accuracy and motion artifacts require further improvements, future enhancements could include wearable integration, AI-based calibration, and improved power efficiency. Overall, this system revolutionizes hemoglobin monitoring, making it faster, safer, and more accessible for widespread use in healthcare.

REFERANCES

[1] Yuan, Y., Zhang, J., Wang, L., & Li, X. "Research on a Non-Invasive Hemoglobin Measurement System Based on Four-Wavelength Photoplethysmography." Electronics 12.6 (2023): 1346.

[2] Li, Y., Wang, Y., Liu, H., & Zhang, X. "A Non-Invasive Hemoglobin Detection Device Based on Multispectral Photoplethysmography." Biosensors 14.1 (2024): 22.

[3] Sordillo, L. A., Sordillo, P. P., & Alfano, R. R. "Noninvasive Hemoglobin Sensing and Imaging: Optical Tools for Disease Diagnosis." Journal of Biomedical Optics 27.8 (2022): 080901.

[4] Kumar, Y., Gupta, D., & Sharma, A. "Estimation of Hemoglobin Using Non-Invasive Portable Device with Spectroscopic Signal Application." Scientific Reports 13 (2023): 58990.

[5] Wu, C., & Tandon, T. "Real-Time Non-Invasive Hemoglobin Prediction Using Deep Learning-Enabled Smartphone Imaging." Scientific Reports 13 (2023): 11218390.

[6] Hasan, M. K., Sakib, N., Field, J., Love, R. R., & Ahamed, S. I. "A Novel Technique of Noninvasive Hemoglobin Level Measurement Using HSV Value of Fingertip Image." arXiv preprint (2019): arXiv:1910.02579.

[7] Zherebtsov, E. A., Potapova, E. V., & Tuchin, V. V. "Non-Invasive Hemoglobin Assessment with NIR Imaging of Blood Vessels in Transmittance Geometry: Monte Carlo and Experimental Evaluation." Photonics 11.1 (2024).