Ear-Wearable SpO_2 and Heart-Rate Monitoring Device for Low-Ventilation Area Workers

Report submitted to GITAM (Deemed to be University) as a partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in (Electrical Electronics and Communication Engineering)

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DECLARATION

We hereby certify that the work presented in this report entitled **"Development of an Ear-Wearable SpO_2 and Heart-Rate Monitoring Device for Low-Ventilation Area Workers"** is the result of original research carried out by the undersigned project team. This report, either in full or in part, has not been submitted previously for the award of any degree or diploma at this or any other institution.

All information derived from published or unpublished work of others has been duly acknowledged and referenced. This project has been carried out under the supervision and guidance of **Dr. Kshitij Shakaya**.

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CERTIFICATE

This is to certify that MONISHA HS (Regd. No.: BU22EECE0100439) and PRAJWAL SHETTY (Regd. No.: BU22EECE0100434) has satisfactorily completed Mini Project Entitled in partial fulfillment of the requirements as prescribed by University for VIIth semester, Bachelor of Technology in "Electrical, Electronics and Communication Engineering" and submitted this report during the academic year 2025-2026.

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Chapter 1: Introduction

1.1 Overview of the problem statement

Workers in low-ventilation environments such as mines, tunnels and sealed industrial facilities are exposed to low oxygen levels and associated health risks. Conventional finger-clip pulse oximeters, although accurate, are impractical for continuous use by mobile workers because they are uncomfortable, restrict movement and are prone to motion artefacts. There is therefore a need for a compact, ear-wearable device that can continuously monitor SpO_2 and heart rate and reliably distinguish between true hypoxia events and spurious signals.

1.2 Objectives and goals

The main objective is to design and prototype an ear-wearable SpO_2 and heart-rate monitoring device for workers in low-ventilation environments, enhanced with machine-learning algorithms to improve reliability and reduce false alarms.

The specific goals of the project are:

- Integrate a MAX3010x optical sensor into an ergonomic ear-clip housing.
- Acquire and process photoplethysmography (PPG) signals for SpO_2 and heart-rate estimation.
- Apply digital filtering and feature extraction to improve signal quality.
- Train a lightweight machine-learning model to differentiate genuine events from noise.
- Provide real-time alerts (LED/buzzer) when unsafe SpO_2 levels are detected and Ensure comfort, portability and low power consumption for extended industrial use.

Chapter 2: Literature Review

1. **"Evaluation of a novel ear pulse oximeter (Oxy Frame)"**
   Authors: Fabian Braun, et al.
   Summary / info: Describes design and validation of an ear-mounted pulse oximeter; reports accuracy (RMS error), test protocol on volunteers, and practical design issues for ear sensors (light coupling, motion). Very useful for understanding measurement error, evaluation metrics, and ear sensor placement.
   Why relevant: Directly demonstrates ear-based SpO_2 feasibility and gives benchmark metrics you can compare to.
   Source: Sensors (MDPI).

2. **"Wearable in-ear pulse oximetry validly measures oxygen saturation between 70% and 100%: A prospective agreement study"**
   Authors: C. A. Bubb, M. Weber, S. Schmid, et al. (2023)
   Summary / info: Prospective study validating an in-ear wearable against reference oximeters; includes clinical agreement statistics and practical limitations. Confirms ear devices can be accurate across a wide SpO_2 range.
   Why relevant: Clinical validation evidence — handy for the "motivation / justification" and for setting accuracy targets.
   Source: Digital Health / PubMed.

3. **"Accurate detection of heart rate using in-ear photoplethysmography in a clinical setting"**
   Authors: T. Adams et al. (2022)
   Summary / info: Compares in-ear PPG against ECG during realistic clinical tasks; discusses SNR, artifact handling, and in-ear placement stability. Includes processing methods that improve heart-rate extraction.
   Why relevant: Gives concrete signal-processing methods for heart-rate extraction from ear PPG — transferable to SpO_2 pipeline.
   Source: PubMed Central (open access).

4. **"EarSet: A multi-modal dataset for studying the impact of movement and device placement on ear-PPG"**
Authors: A. Montanari, et al. (2023)
Summary / info: Provides a curated dataset and analysis of ear PPG with simultaneous motion/annotations — useful to study motion artifacts and algorithm robustness.
Why relevant: Real dataset you can use for ML experiments or to compare features and artifact types.
Source: Nature Scientific Data (dataset paper).

5. **"Photoplethysmography signal processing and synthesis"** (chapter / review)
Authors: Peter H. Charlton / collaborators (comprehensive chapter)
Summary / info: In-depth review of PPG fundamentals, filtering, AC/DC separation, feature extraction, and methods for synthesizing PPG signals. Great reference for building preprocessing pipelines.
Why relevant: Foundational reading for every step of your signal chain (filter design, beat detection, perfusion index).
**Source / PDF available online.

6. **"SPECMAR: Fast heart-rate estimation from PPG using modified spectral subtraction with composite motion artifact reference"**
Authors: M. Islam et al. (2018)
Summary / info: Motion-artifact robust heart-rate estimation algorithm using spectral subtraction; demonstrates improved HR extraction during movement.
Why relevant: Offers a concrete artifact-removal algorithm you can adapt for ear PPG preprocessing before SpO_2 estimation.
Source: arXiv / preprint.

7. **"PPG motion-artifact removal using generative models (CycleGAN)"**
   Authors: Zargari et al. (2021)
   Summary / info: Uses CycleGAN (a generative adversarial technique) to transform noisy PPG into cleaner PPG without requiring accelerometer data. Shows promise where accelerometer may be noisy or unavailable.
   Why relevant: Advanced technique for artifact reduction if you want to experiment beyond classical filters/regressors.
   Source: arXiv / preprint.

8. **"A review of deep-learning methods for photoplethysmography data"**
   Authors: Guangkun Nie, Jiabao Zhu, et al. (2024)
   Summary / info: Comprehensive survey of deep learning applications applied to PPG (SpO_2 prediction, HR estimation, signal quality classification, respiration/HRV tasks). Summarizes datasets, model types, common pitfalls (data scarcity, generalization).
   Why relevant: Excellent roadmap of the ML methods you can try and pitfalls to avoid (overfitting, domain shift).
   Source: arXiv (open access).

Chapter 3 : Strategic Analysis and Problem Definition

3.1 SWOT Analysis

Strengths

• Ear location gives stable PPG signals with faster response to oxygen changes.
• MAX3010x sensor is compact, low-cost and low-power.
• Machine-learning integration reduces false alarms and improves reliability.
• Non-intrusive, comfortable design suitable for continuous monitoring.

Weaknesses

- Prototype still under development.
- Requires sufficient labelled data for ML training.
- Accuracy may be affected in extreme conditions (sweat, temperature).

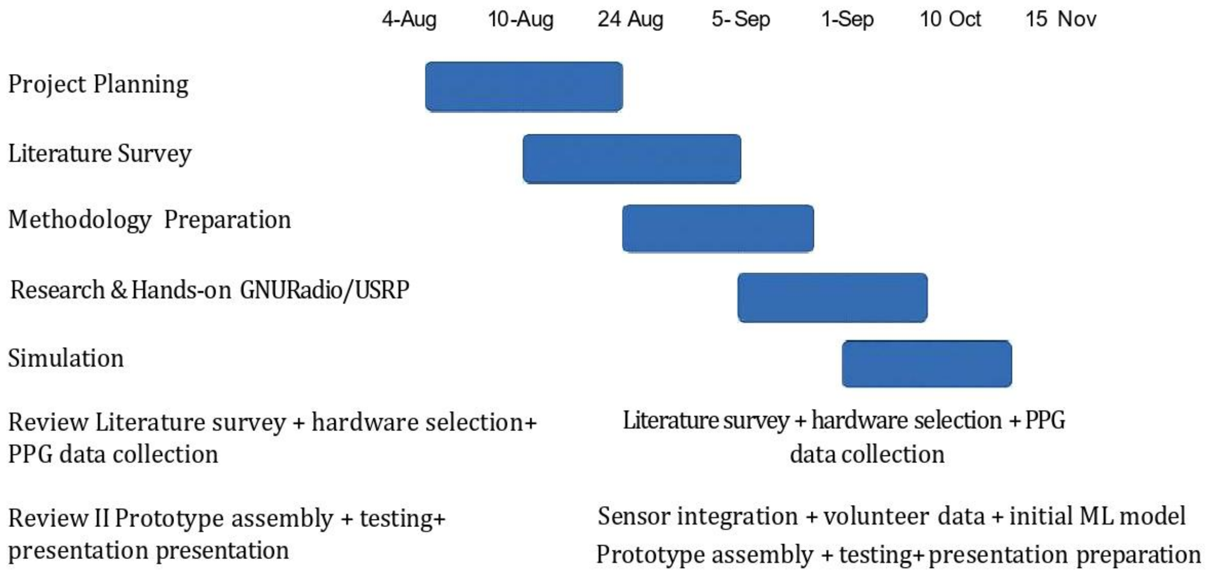
Opportunities

- Increasing demand for worker safety devices in mining, tunnelling, aerospace and healthcare.
- Potential for integration with IoT/cloud dashboards and predictive analytics.
- Expandable to monitor additional vital signs (temperature, respiration).

Threats

- Competition from established commercial wearable manufacturers.
- Rapid technology changes may make chosen components obsolete.
- Regulatory approval requirements for health devices may delay deployment.

3.2 Project Plan - GANTT Chart



3.3 Problem statement

Workers in confined or low-ventilation environments such as underground mines, tunnels and sealed industrial facilities are exposed to increased risk of hypoxia due to insufficient oxygen availability. Existing pulse oximeters are typically finger-clip devices designed for stationary, short-term measurement. They are uncomfortable, restrict hand movement, and are highly susceptible to motion artefacts, making them unsuitable for continuous monitoring of mobile workers.

The problem addressed by this project is the absence of a **compact, non-intrusive and reliable wearable SpO_2 monitoring device** specifically designed for industrial workers. The project aims to design and prototype an **ear-wearable pulse oximeter** using a MAX3010x optical sensor and a microcontroller, enhanced with machine-learning techniques to differentiate between genuine low-oxygen events and false readings caused by noise or motion. The device will provide real-time alerts to the worker and optionally transmit data wirelessly to supervisors, thereby improving workplace safety in hazardous, low-ventilation environments.

Chapter 4: Methodology

4.1 Description of the Approach

The proposed system combines a low-cost optical sensor with a microcontroller and a machine-learning pipeline to deliver reliable SpO_2 and heart-rate measurements from the ear.

The overall workflow is as follows:

- **Sensor Integration:** A MAX3010x (MAX30100/MAX30102) pulse-oximeter module will be mounted in an ergonomically designed ear-clip housing. This location is chosen because the ear lobe has good blood perfusion and is less affected by hand movement, leading to more stable photoplethysmography (PPG) signals.
- **Signal Acquisition:** The microcontroller (Arduino Nano or ESP32) continuously samples raw red and infrared light absorption values from the MAX3010x sensor.
- **Pre-processing:** Digital filters (moving average, low-pass Butterworth, baseline wander removal) are applied to remove ambient light interference and motion artefacts.
- **Feature Extraction:** From the cleaned PPG waveform, features such as AC/DC ratios, peak intervals, amplitude variability, and heart-rate variability are computed.
- **Machine-Learning Classification:** Using Python/scikit-learn, a model is trained on labelled data (normal readings vs. true low-oxygen events vs. noise) to distinguish genuine hypoxia from false alarms caused by movement or poor contact.
- **Alert Generation:** When the ML model detects a verified low SpO_2 event, the microcontroller activates visual (LED) and/or acoustic (buzzer) indicators for immediate warning. Optionally, the data are transmitted wirelessly to a supervisor’s dashboard.
- **Validation:** The device’s outputs will be compared with a reference pulse oximeter under different conditions (rest, mild motion, simulated low oxygen) to assess accuracy and false-alarm rate.This staged approach allows iterative development: first, signal acquisition and basic thresholding; second, ML model training with stored data; third, real-time embedded classification.

4.2 Tools and Techniques Utilized

Hardware Components:

- MAX3010x optical pulse-oximeter sensor module.
- Arduino Nano / ESP32 development board for data acquisition and processing.
- Ear-clip housing for sensor placement.
- Buzzer and LED indicators for alerts.
- Optional Bluetooth or Wi-Fi module for wireless transmission.

Software & Programming Tools:

- **Arduino IDE** – programming the microcontroller to read sensor data and trigger alerts.
- **Python** – for offline data analysis and machine-learning model development.
- **Libraries:**

NumPy and Pandas for data manipulation.
Matplotlib for visualization of PPG waveforms.
SciPy for digital filter design.
Scikit-learn for training and evaluating ML classifiers.
Jupyter Notebook for experimentation.

- **Signal Processing Techniques:**

Low-pass and high-pass filtering to remove noise and baseline drift.
Peak detection algorithms for heart-rate calculation.
Calculation of AC/DC ratio of red/IR signals for SpO_2 estimation.

- **Machine-Learning Techniques:**

Logistic Regression, Random Forest or Support Vector Machine for binary classification (true vs. false event).
Cross-validation to assess model robustness.
Model export to lightweight format for embedded use.

4.3 Design Considerations

- **Sensor Placement and Ergonomics:** The ear-clip must be lightweight, non-obtrusive and adjustable to different ear sizes to ensure comfort during long shifts and good optical coupling with skin.
- **Power Consumption:** The device should use low-power modes of the MAX3010x and microcontroller to enable extended operation on a small battery.
- **Sampling Rate and Memory:** A balance between high enough sampling frequency for accurate SpO_2 estimation and low enough data rate to conserve power and storage.
- **Motion Artefact Robustness:** Inclusion of filtering and ML-based artefact detection to maintain accuracy during worker movement.
- **User Safety and Alerting:** The alert system (LED/buzzer) must be clearly perceivable in noisy environments and not cause discomfort.
- **Scalability and Connectivity:** Provision for adding wireless transmission (Bluetooth Low Energy / Wi-Fi) so that supervisors can monitor multiple workers simultaneously on a dashboard.
- **Cost and Manufacturability:** Selection of components that are affordable and widely available for ease of prototyping and scaling up.

Chapter 5: Implementation

5.1 Description of how the project was executed

5.2 Challenges faced and solutions implemented

Chapter 6: Results

6.1 outcomes

6.2 Interpretation of results

6.3 Comparison with existing literature or technologies

Chapter 7: Conclusion

Chapter 8 : Future Work

References:

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