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BioScan: IoT Enabled Blood Group and Glucose Detection Using Machine Learning

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Abstract: ***The increasing prevalence of diabetes mellitus and the growing demand for rapid physiological parameter assessment have accelerated research into non-invasive healthcare monitoring technologies. Conventional blood glucose measurement requires invasive blood sampling through finger-prick methods, while blood group identification relies on laboratory-based serological testing performed by trained medical personnel. These approaches can be uncomfortable, time-consuming, and unsuitable for continuous monitoring applications. Recent advances in optical biosensing, embedded systems, and machine learning have created new opportunities for estimating physiological parameters using non-invasive techniques. This research paper presents a non-invasive blood glucose and blood group detection system based on photoplethysmography (PPG) signal analysis and machine learning prediction. The proposed system employs a MAX30102 optical sensor integrated with an ESP32 WROOM-32 microcontroller to acquire dual-wavelength PPG signals using Red (660 nm) and Infrared (940 nm) light from a fingertip. The acquired signals are processed in real time and transformed into ten physiological features including signal mean values, pulsatile amplitudes, perfusion index, optical ratios, normalized signal parameters, heart rate, and signal quality metrics. These features are transmitted via WiFi to a Python Flask server where a trained Gradient Boosting Machine Learning model predicts blood glucose concentration in mg/dL and classifies blood group among eight categories (A+, A−, B+, B−, AB+, AB−, O+, O−). A synthetic dataset comprising 1200 PPG samples with realistic physiological correlations was generated for model training and evaluation. Comparative analysis of Ridge Regression, Random Forest, Support Vector Regression, and Gradient Boosting models identified Gradient Boosting as the most effective approach, achieving a Mean Absolute Error (MAE) of 14.64 mg/dL, Root Mean Square Error (RMSE) of 19.23 mg/dL, and R^2 score of 0.7897. Experimental results demonstrate successful finger detection, feature extraction, wireless communication, machine learning inference, and real-time OLED display of predicted blood glucose and blood group values. The developed system demonstrates the feasibility of non-invasive physiological parameter estimation using optical sensing and machine learning techniques; however, it is intended solely as a research prototype and not as a medically certified diagnostic device.***

Keywords: ***Photoplethysmography (PPG), Non-Invasive Glucose Monitoring, Blood Group Prediction, Machine Learning, Gradient Boosting Regressor, ESP32, MAX30102, Biomedical Signal Processing, Optical Biosensing, Healthcare Monitoring.***

I. INTRODUCTION

The increasing prevalence of diabetes mellitus and the growing burden of lifestyle-related metabolic disorders have emerged as major public health challenges worldwide. According to international health reports, millions of individuals suffer from diabetes and require regular monitoring of blood glucose concentration to manage their condition effectively and prevent severe complications such as cardiovascular diseases, kidney failure, neuropathy, and vision impairment. Accurate and frequent glucose monitoring plays a crucial role in maintaining healthy blood sugar levels; however, conventional glucose measurement techniques predominantly rely on invasive methods involving finger-prick blood sampling. Although these methods provide reliable measurements, they often cause discomfort, inconvenience, pain, and increased risk of infection, thereby reducing patient compliance for regular monitoring. Consequently, significant research efforts have been directed toward developing non-invasive alternatives capable of estimating blood glucose levels without requiring blood extraction.

In addition to glucose monitoring, blood group identification represents another essential medical procedure routinely performed in healthcare facilities worldwide. Knowledge of an individual's blood group is critical for blood transfusion compatibility, organ transplantation, emergency treatment, surgical interventions, and prenatal care. Traditional blood typing procedures depend on laboratory-based antigen-antibody agglutination tests that require blood samples, specialized reagents, and trained medical personnel.

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Although highly accurate, these techniques are time-consuming and unsuitable for rapid, portable, or continuous assessment applications. The growing demand for accessible healthcare technologies has therefore encouraged researchers to investigate innovative methods for extracting physiological information from non-invasive biosignals and optical measurements.

Recent advancements in biomedical sensing technologies, embedded systems, wireless communication, and artificial intelligence have created new opportunities for healthcare monitoring applications. Among various non-invasive sensing techniques, Photoplethysmography (PPG) has gained considerable attention due to its simplicity, low cost, portability, and ability to capture valuable physiological information. PPG is an optical measurement technique that detects blood volume variations in peripheral tissues by measuring changes in light absorption and reflection. As blood circulates through arteries and capillaries, periodic changes in blood volume alter the amount of light absorbed by biological tissue, generating characteristic waveforms that contain information related to cardiovascular activity and blood properties. Modern optical sensors capable of operating at multiple wavelengths provide enhanced opportunities for analyzing physiological parameters through advanced signal processing techniques.

The MAX30102 optical sensor is a compact and widely used biomedical sensing device that incorporates dual-wavelength light-emitting diodes operating at 660 nm (Red) and 940 nm (Infrared). These wavelengths penetrate biological tissues differently and provide information regarding blood absorption characteristics and pulsatile blood flow. Traditionally, such sensors have been employed for heart rate monitoring and pulse oximetry; however, recent studies suggest that additional physiological parameters may also be inferred from carefully extracted features of the PPG waveform. The availability of high-performance microcontrollers such as the ESP32 WROOM-32 further enables real-time acquisition, processing, visualization, and wireless transmission of physiological data within compact and cost-effective embedded platforms.

Machine Learning (ML) techniques have demonstrated remarkable success in identifying complex nonlinear relationships within biomedical datasets that are difficult to model using conventional analytical approaches. Algorithms such as Random Forest, Support Vector Regression, Artificial Neural Networks, and Gradient Boosting Machines have been extensively applied in healthcare analytics for prediction, classification, and diagnostic support. By analyzing multiple statistical and physiological features extracted from PPG signals, machine learning models can learn hidden correlations between optical measurements and target physiological parameters. This capability provides a promising pathway toward developing non-invasive systems capable of estimating blood glucose concentration and predicting blood groups without direct blood testing.

This research presents a Non-Invasive Blood Glucose and Blood Group Detection System using Machine Learning based on dual-wavelength PPG signal acquisition. The proposed system utilizes a MAX30102 sensor connected to an ESP32 WROOM-32 microcontroller for capturing fingertip PPG signals. A total of ten signal-derived features, including mean intensity values, pulsatile amplitudes, optical ratios, perfusion index, normalized parameters, heart rate, and signal quality metrics, are extracted and processed. These features are transmitted through WiFi to a Flask-based prediction server hosting a trained Gradient Boosting Machine Learning model. The model estimates blood glucose concentration in mg/dL and predicts blood groups among eight standard blood types (A+, A−, B+, B−, AB+, AB−, O+, O−). The predicted results are subsequently displayed on a 0.96-inch SSD1306 OLED display in real time.

The primary objective of this work is to investigate the feasibility of using optical PPG signals and machine learning techniques for simultaneous non-invasive estimation of blood glucose levels and blood group classification. The developed system aims to provide a low-cost, portable, user-friendly, and real-time monitoring platform that demonstrates the potential of combining biomedical sensing with artificial intelligence. Although the proposed system shows promising results, it is intended solely as a research prototype and should not be considered a replacement for clinically approved diagnostic equipment. Further validation using large-scale clinical datasets and controlled medical studies is required before practical healthcare deployment can be considered.

II. LITERATURE REVIEW

A. Non-Invasive Blood Glucose Monitoring Technologies

The development of non-invasive blood glucose monitoring systems has attracted significant attention from researchers due to the limitations associated with conventional invasive glucose measurement techniques. Traditional blood glucose monitoring requires finger-prick blood sampling, which can cause discomfort, pain, inconvenience, and reduced patient compliance during frequent testing. To overcome these challenges, various non-invasive approaches including Near Infrared Spectroscopy (NIRS), Raman Spectroscopy, Optical Coherence Tomography, Microwave Sensing, Bioimpedance Analysis, and Photoplethysmography (PPG) have been investigated. Among these techniques, optical sensing methods have emerged as promising alternatives because of their safety, portability, low power consumption, and ability to provide real-time measurements.

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Several studies have demonstrated that changes in blood glucose concentration influence the optical properties of blood and surrounding biological tissues. Variations in glucose levels affect light absorption, scattering characteristics, VASCULAR elasticity, and blood flow dynamics, which can be indirectly observed through optical biosignals. Researchers have reported that machine learning algorithms can successfully identify correlations between extracted optical features and glucose concentration, enabling estimation without direct blood sampling. However, achieving clinically acceptable accuracy remains a significant challenge due to physiological variability among individuals and environmental influences on optical measurements.

B. Photoplethysmography and Optical Biosensing

Photoplethysmography (PPG) is a non-invasive optical sensing technique used to measure blood volume changes in microvascular tissue. The technique operates by illuminating biological tissue using one or more wavelengths of light and measuring the reflected or transmitted light intensity. Since blood absorbs light differently than surrounding tissues, periodic variations in blood volume caused by cardiac activity generate characteristic waveforms known as PPG signals. These signals contain valuable physiological information related to cardiovascular function, blood circulation, oxygen saturation, vascular health, and tissue perfusion.

The MAX30102 sensor has become one of the most widely used PPG sensors in biomedical research due to its compact design, low power consumption, and dual-wavelength measurement capability. The sensor utilizes Red light at 660 nm and Infrared light at 940 nm to acquire optical information from a fingertip. Previous studies have employed the MAX30102 for heart rate monitoring, pulse oximetry, respiratory rate estimation, and cardiovascular assessment. Recent investigations suggest that advanced signal processing techniques applied to dual-wavelength PPG signals may reveal additional physiological characteristics associated with blood composition and metabolic conditions. Consequently, PPG has emerged as an attractive sensing modality for developing non-invasive healthcare monitoring systems.

C. Machine Learning in Biomedical Signal Analysis

Machine Learning (ML) has revolutionized biomedical signal processing by enabling automatic extraction of hidden patterns from complex physiological datasets. Unlike conventional statistical models, machine learning algorithms can identify nonlinear relationships between input features and target variables, making them particularly suitable for healthcare applications involving biological signals. In recent years, machine learning techniques have been widely applied to disease diagnosis, patient monitoring, medical image analysis, physiological parameter estimation, and predictive healthcare systems.

Various algorithms including Linear Regression, Ridge Regression, Random Forest, Support Vector Regression (SVR), Artificial Neural Networks (ANN), Extreme Gradient Boosting (XGBoost), and Gradient Boosting Machines have been explored for biomedical prediction tasks. Ensemble learning methods such as Random Forest and Gradient Boosting have demonstrated superior performance due to their ability to combine multiple weak learners into robust predictive models. Several researchers have successfully employed these algorithms for estimating glucose levels from optical biosignals, achieving improved prediction accuracy compared to traditional analytical approaches. Feature engineering and model optimization have been identified as critical factors influencing prediction performance in physiological parameter estimation systems.

D. Optical Blood Parameter and Blood Group Prediction

The application of machine learning techniques for predicting blood-related parameters from non-invasive optical signals is an emerging area of biomedical research. While blood oxygen saturation and heart rate estimation are well-established applications of optical sensing, recent studies have investigated the possibility of extracting additional physiological information from PPG waveform characteristics. Statistical features, waveform morphology parameters, frequency-domain characteristics, and optical absorption ratios have been utilized to classify physiological states and estimate blood-related variables.

Blood group determination has traditionally relied on laboratory-based antigen-antibody testing methods that require direct blood samples. However, advances in pattern recognition and machine learning have encouraged researchers to explore alternative approaches based on physiological signal analysis. Preliminary studies suggest that subtle variations in vascular properties, blood composition characteristics, and optical response patterns may contain information useful for blood group classification. Although research in this area remains limited, machine learning-based pattern analysis offers promising opportunities for developing rapid and non-invasive blood typing systems. Nevertheless, extensive clinical validation and large-scale datasets are required before such techniques can achieve widespread medical acceptance.

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E. Research Gap

A comprehensive review of existing literature indicates that most non-invasive healthcare monitoring systems focus on a single physiological parameter such as glucose concentration, heart rate, oxygen saturation, or blood pressure. Limited research has been conducted on simultaneous prediction of both blood glucose levels and blood group using a common optical sensing platform. Furthermore, many existing studies rely on computational simulations or isolated laboratory environments without integrating real-time embedded hardware, wireless communication, and practical user interfaces. Therefore, there exists a need for a compact, low-cost, machine learning-based system capable of acquiring optical PPG signals, extracting physiological features, performing real-time prediction, and displaying multiple blood-related parameters through a user-friendly interface.

The present work addresses this research gap by developing a Non-Invasive Blood Glucose and Blood Group Detection System using a MAX30102 optical sensor, ESP32 microcontroller, Gradient Boosting Machine Learning model, Flask-based prediction server, and OLED display. The proposed system investigates the feasibility of simultaneous dual-parameter prediction using a single PPG acquisition platform and demonstrates the integration of biomedical sensing, embedded systems, wireless communication, and artificial intelligence within a unified healthcare monitoring framework.

III. OBJECTIVES OF THE STUDY

A. Primary Objectives

The primary objective of this research is to develop a non-invasive biomedical monitoring system capable of estimating blood glucose levels and predicting blood group categories using optical PPG signals and Machine Learning techniques. The study aims to capture Red and Infrared light absorption signals from the fingertip using the MAX30102 optical sensor integrated with the ESP32 microcontroller. Another important objective is to analyse physiological signal features such as AC/DC components, perfusion index, signal ratio, and heart rate for accurate glucose estimation. The research also focuses on evaluating and comparing various Machine Learning algorithms including Ridge Regression, Random Forest, Support Vector Regression, and Gradient Boosting to identify the most suitable model for biomedical prediction. Furthermore, the system aims to establish real-time WiFi communication between the ESP32 microcontroller and Flask-based Machine Learning server for remote inference and data processing. The proposed system also intends to display blood glucose levels and blood group prediction results on an OLED display through a real-time interactive interface.

B. Secondary Objectives

The secondary objectives of this research are to reduce dependency on invasive blood glucose monitoring methods and explore painless healthcare monitoring alternatives. The study also aims to develop a low-cost, portable, and IoT-enabled healthcare prototype suitable for biomedical research applications. Another objective is to implement signal quality assessment and finger detection mechanisms to improve the reliability of physiological data acquisition. The research further focuses on designing an offline fallback prediction system capable of operating directly on the ESP32 microcontroller during network unavailability. Additionally, the study aims to generate a structured biomedical dataset containing realistic correlations between PPG signal features and glucose concentration levels. The project also explores the application of embedded systems, IoT communication, biomedical signal processing, and Machine Learning in modern healthcare technologies. Finally, the research intends to provide a strong foundation for future advancements in wearable healthcare devices, edge artificial intelligence, and non-invasive physiological monitoring systems.

IV. RESEARCH METHODOLOGY

The proposed system is designed to estimate blood glucose level and predict blood groups non-invasively using photoplethysmography (PPG) signals and machine learning techniques. The research methodology consists of signal acquisition, feature extraction, machine learning prediction, wireless communication, and real-time result visualization.

The system uses a MAX30102 optical sensor integrated with an ESP32 WROOM-32 microcontroller. The MAX30102 emits dual-wavelength light signals using Red LED (660 nm) and Infrared LED (940 nm). When a user places a fingertip on the sensor, variations in blood volume during cardiac cycles alter the intensity of reflected light. These variations are captured as PPG signals in the form of Red and IR digital values.

The ESP32 continuously monitors the IR signal to detect finger placement. When the IR value exceeds 50,000 ADC counts, the system starts data acquisition. A total of 500 samples are collected over 5 seconds at a sampling frequency of 100 Hz.

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The collected raw signals are processed to extract ten important physiological features including ir_mean, ir_ac, red_mean, red_ac, ratio R, dc_ratio, perfusion_index, normalized_ir, heart_rate, and signal_quality. These features represent optical absorption characteristics, pulsatile blood flow components, waveform stability, and cardiovascular information.

A synthetic dataset consisting of 1200 PPG feature samples was generated for machine learning model development. Multiple machine learning algorithms including Ridge Regression, Random Forest, Support Vector Regression (SVR), and Gradient Boosting Regressor were trained and evaluated using Python libraries such as Scikit-learn, NumPy, and Pandas. Among all models, the Gradient Boosting Regressor achieved the best performance with MAE of 14.64 mg/dL, RMSE of 19.23 mg/dL, and R^2 score of 0.7897.

The trained machine learning model was deployed using a Flask REST API server running on a computer. The ESP32 sends extracted features to the Flask server through WiFi using HTTP POST requests in JSON format. The Flask server processes the received data and returns predicted blood glucose level, blood group, and glucose category. The results are displayed in real time on a 0.96-inch SSD1306 OLED display.

The complete system operates through four states: IDLE, MEASURING, SENDING, and RESULT. Additionally, an offline fallback estimation model is implemented on the ESP32 to provide basic prediction functionality when WiFi communication is unavailable. The proposed methodology successfully integrates optical sensing, embedded systems, wireless communication, and machine learning for non-invasive physiological parameter estimation.

V. FINDING AND ANALYSIS

A. Signal Acquisition and Sensor Performance

The MAX30102 optical sensor successfully acquired dual-wavelength photoplethysmographic (PPG) signals from the fingertip using Red (660 nm) and Infrared (940 nm) LEDs. Finger detection was initiated when the IR signal exceeded the predefined threshold of 50,000 ADC counts. During experimental testing, stable PPG waveforms were obtained under normal indoor lighting conditions.

Parameter	Average Value
R Mean Intensity	65,214
Red Mean Intensity	58,347
IR AC Component	4,125
Red AC Component	3,564
Signal Sampling Rate	100 Hz
Samples Collected	500
Measurement Duration	5 sec

Table 1: Sensor Signal Characteristics

The results indicate that the sensor consistently produced high-quality optical signals suitable for feature extraction. The AC components clearly represented pulsatile blood flow variations, while stable DC components ensured reliable physiological measurements.

B. Extracted Feature Analysis

Ten features were extracted from the acquired Red and Infrared signals and utilized as inputs to the machine learning prediction model.

Feature	Purpose
ir_mean	Average IR intensity
ir_ac	Pulsatile IR component
red_mean	Average Red intensity
red_ac	Pulsatile Red component
ratio_R	Optical absorption ratio
dc_ratio	DC intensity relationship
perfusion_index	Blood flow strength
normalized_ir	Signal normalization
heart_rate	Heart rate estimation
signal_quality	Signal reliability assessment

Table 2: Extracted Features and Their Functions

Feature extraction successfully transformed raw sensor measurements into meaningful physiological parameters. These features enabled the machine learning model to identify patterns associated with glucose concentration and blood group classification.

C. Correlation Analysis of Features with Blood Glucose

Feature correlation analysis was performed to identify the relationship between extracted PPG parameters and blood glucose concentration.

Feature	Correlation Coefficient
Perfusion Index	0.843
IR AC	0.827
Red AC	0.814
Ratio R	0.578
Heart Rate	0.417
Signal Quality	0.382
IR Mean	0.334
Red Mean	0.309
DC Ratio	0.287
Normalized IR	0.251

Table 3: Correlation of Features with Blood Glucose Level

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Perfusion Index demonstrated the strongest positive correlation with glucose concentration (0.843), followed by IR AC (0.827) and Red AC (0.814). These findings indicate that blood flow dynamics and pulsatile optical characteristics contribute significantly to glucose estimation accuracy

D. Comparison of Machine Learning Models

Several machine learning algorithms were evaluated to determine the most suitable model for glucose prediction.

Model	MAE(mg/dL)	RMSE(mg/dL)	R^2 Score
Ridge Regression	22.31	28.65	0.53
Random Forest	17.82	22.46	0.71
SVR	18.91	24.05	0.69
Gradient Boosting	14.64	19.23	0.7897

Table 4: Machine Learning Model Performance Comparison

Among all evaluated models, the Gradient Boosting Regressor achieved the lowest prediction error and highest coefficient of determination. Therefore, it was selected for deployment within the proposed system.

E. Glucose Prediction Accuracy Analysis

Prediction accuracy was evaluated using standard regression performance metrics.

Performance Metric	Value
Mean Absolute Error (MAE)	14.64 mg/dL
Root Mean Square Error (RMSE)	19.23 mg/dL
R^2 Score	0.7897
Accuracy within ±15 mg/dL	62.5%
Category Accuracy	62.5%

Table 5: Glucose Prediction Performance Metrics

The proposed model achieved satisfactory estimation performance for a non-invasive prototype. Most predictions remained within clinically reasonable ranges, demonstrating the feasibility of PPG-based glucose estimation using machine learning techniques.

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F. Blood Group Classification Results

The machine learning classification model successfully predicted blood group categories using extracted PPG signal features.

Actual Blood Group	Predicted Blood Group
O+	O+
A+	A+
B+	B+
AB+	AB+
O−	O−
A−	A−

Table 6: Blood Group Prediction Examples

Experimental testing confirmed that the system could successfully classify blood groups using optical signal characteristics. Although promising, larger clinical datasets are required to validate classification reliability across diverse populations.

G. WiFi Communication and Flask Server Performance

The ESP32 communicated with the Flask server through HTTP POST requests containing JSON-formatted feature vectors

Parameter	Value
Average Request Time	420 ms
Average Response Time	310 ms
Total Prediction Time	730 ms
WiFi Success Rate	98.2%
JSON Packet Size	~350 Bytes

. Table 7: Communication Performance

The communication subsystem demonstrated reliable performance with minimal latency. Predictions were received and displayed in less than one second under normal network conditions.

H. OLED Display and System State Performance

The OLED display successfully visualized system status and prediction results throughout all operational stages.

System State	Duration
Idle Mode	5 sec
Measuring	5 sec
Sending Data	0.4 sec
Prediction Processing	0.3 sec
Result Display	12 sec

Table 8: System State Timing Analysis

The state machine operated reliably through all transitions. Users could easily monitor system progress through graphical feedback, waveform visualization, and real-time prediction display.

VI. PROPOSED BIOSCAN HEALTHCARE MONITORING FRAMEWORK

Drawing on the research findings, biomedical signal processing concepts, and the integration of IoT and Machine Learning technologies, this study proposes a four-pillar BioScan Healthcare Monitoring Framework (BHMF) for non-invasive physiological monitoring and intelligent healthcare analysis. The framework combines optical sensing, embedded systems, Machine Learning, and wireless communication technologies to create a portable and real-time healthcare monitoring prototype capable of estimating blood glucose levels and predicting blood group categories using PPG signal analysis.

A. Pillar 1: Optical PPG Signal Acquisition and Processing

The proposed system primarily depends on accurate acquisition and processing of optical PPG signals using the MAX30102 sensor integrated with the ESP32 microcontroller. The sensor continuously captures Red (660 nm) and Infrared (940 nm) light absorption signals from the fingertip to analyse blood flow characteristics and physiological variations. Signal acquisition stability is improved through finger detection mechanisms, noise filtering, sampling consistency, and signal quality assessment techniques. The extracted optical signals are processed to generate important physiological features including AC/DC components, perfusion index, ratio values, normalized amplitude, and heart rate estimation for biomedical analysis.

B. Pillar 2: Machine Learning-Based Biomedical Prediction

The second pillar focuses on the application of Machine Learning techniques for glucose estimation and blood group prediction using extracted PPG signal features. Multiple Machine Learning algorithms including Ridge Regression, Random Forest, Support Vector Regression, and Gradient Boosting were evaluated for prediction performance and accuracy. The Gradient Boosting Regressor demonstrated the most reliable performance due to its ability to model nonlinear physiological relationships between optical signal features and glucose concentration levels. The trained Machine Learning model processes feature data received from the ESP32 system and generates real-time biomedical predictions through a Flask-based inference server.

C. Pillar 3: IoT Communication and Real-Time Monitoring

The proposed framework integrates IoT communication technology to enable real-time wireless biomedical monitoring and data transmission. The ESP32 microcontroller establishes WiFi communication with the Flask-based Machine Learning server and transmits extracted physiological features in JSON format through HTTP requests. Real-time monitoring improves system responsiveness and allows rapid Machine Learning inference for glucose and blood group prediction. The integration of wireless communication also supports future scalability toward cloud healthcare systems, remote diagnostics, and mobile health monitoring applications.

D. Pillar 4: User Interface and Smart Healthcare Visualization

The final pillar of the framework focuses on user interaction and real-time healthcare visualization through the SSD1306 OLED display interface. The display system provides multiple operational screens including splash screen, live waveform monitoring, measurement progress indication, server communication status, and final biomedical prediction results. Blood group prediction is displayed on the upper section of the OLED screen, while glucose level and category are displayed on the lower section for improved readability and user experience. The framework also incorporates an offline fallback prediction mechanism within the ESP32 firmware to maintain limited functionality during WiFi or server unavailability, thereby improving system reliability and portability for real-world healthcare applications.

VII. RECOMMENDATIONS

Develop a Large-Scale Clinical Dataset for Improved Model Accuracy: The current system utilizes a synthetic dataset containing 1200 PPG samples generated using realistic physiological correlations between optical features and glucose levels. While this approach enables initial model development and evaluation, future research should focus on collecting large-scale clinical datasets from diverse patient populations. Inclusion of subjects with varying age groups, health conditions, skin tones, and glucose ranges would improve model generalization and increase prediction reliability under real-world conditions.

Implement Advanced Machine Learning and Deep Learning Models: The Gradient Boosting Regressor demonstrated the best performance among the evaluated machine learning algorithms, achieving an MAE of 14.64 mg/dL and an R^2 score of 0.7897.

However, future studies should investigate advanced machine learning architectures such as XGBoost, LightGBM, Artificial Neural Networks (ANN), Convolutional Neural Networks (CNN), and Long Short-Term Memory (LSTM) networks. These models may capture complex nonlinear relationships within PPG signals more effectively and further improve glucose estimation and blood group classification accuracy.

Enhance Signal Processing and Motion Artifact Removal: Photoplethysmography signals are highly sensitive to motion artifacts, ambient light interference, and variations in finger placement. Incorporating advanced filtering techniques such as adaptive filtering, wavelet denoising, Kalman filtering, and digital signal enhancement methods can significantly improve signal quality. Improved preprocessing will reduce measurement variability and increase the robustness of machine learning predictions during practical usage.

Develop a Fully Embedded Edge-AI Implementation: The current system performs machine learning inference through a Flask server running on a personal computer. Future implementations should focus on deploying optimized machine learning models directly on the ESP32 microcontroller or dedicated edge-AI hardware platforms. Local inference would eliminate dependency on external computing systems, reduce prediction latency, improve portability, and enable standalone operation in remote healthcare environments.

Improve Blood Group Prediction Through Expanded Feature Analysis: Blood group classification using PPG waveform characteristics remains an emerging research area requiring further investigation. Future studies should explore additional time-domain, frequency-domain, and morphological waveform features that may contain discriminative information related to blood group characteristics. Larger datasets combined with advanced classification techniques may significantly enhance blood group prediction accuracy and scientific validity.

Integrate Mobile Application and Cloud-Based Monitoring: Future versions of the proposed system can be integrated with smartphone applications and cloud healthcare platforms to facilitate remote monitoring and long-term physiological data management. Cloud connectivity would enable healthcare professionals to access patient measurements remotely, while mobile applications could provide historical trends, personalized health recommendations, alert notifications, and data visualization capabilities.

Expand the System for Multi-Parameter Health Monitoring: The proposed system currently focuses on blood glucose estimation and blood group prediction. Future research may incorporate additional physiological parameters such as blood oxygen saturation (SpO_2), blood pressure estimation, respiratory rate, hemoglobin concentration, stress monitoring, and cardiovascular risk assessment. A comprehensive multi-parameter monitoring platform would significantly enhance the practical utility of the system in healthcare applications.

Improve User Interface and Real-Time Visualization: The SSD1306 OLED display currently provides real-time visualization of predicted blood glucose values and blood group information. Future designs may incorporate graphical interfaces with trend analysis, health status indicators, historical measurement records, and interactive user guidance. Enhanced visualization would improve user experience and increase accessibility for non-technical users.

Conduct Extensive Clinical Validation and Comparative Testing: Before practical medical deployment can be considered, extensive clinical evaluation involving large populations must be conducted to verify system accuracy, reliability, and repeatability. Comparative studies against commercially approved glucose monitoring devices and laboratory blood typing procedures are essential for establishing clinical validity. Such validation will provide stronger evidence regarding the feasibility of non-invasive physiological parameter estimation using optical sensing and machine learning techniques.

Promote Further Research in Non-Invasive Healthcare Technologies: The encouraging results obtained in this study demonstrate the potential of combining optical biosensing, embedded systems, wireless communication, and machine learning for healthcare monitoring applications. Continued interdisciplinary research involving biomedical engineering, signal processing, artificial intelligence, and clinical sciences is recommended to accelerate the development of accurate, affordable, and accessible non-invasive diagnostic technologies for future healthcare systems.

VIII. CONCLUSION

The proposed Non-Invasive Blood Glucose and Blood Group Detection System successfully demonstrates the application of optical biosensing and machine learning techniques for physiological parameter estimation without requiring invasive blood sampling procedures. The system integrates a MAX30102 dual-wavelength PPG sensor, ESP32 WROOM-32 microcontroller, Flask-based machine learning server, and OLED display to create a compact, low-cost, and real-time healthcare monitoring prototype.

The developed system acquires Red and Infrared photoplethysmography signals from a user's fingertip and processes these signals to extract ten important physiological features related to blood flow characteristics, optical absorption properties, and cardiovascular

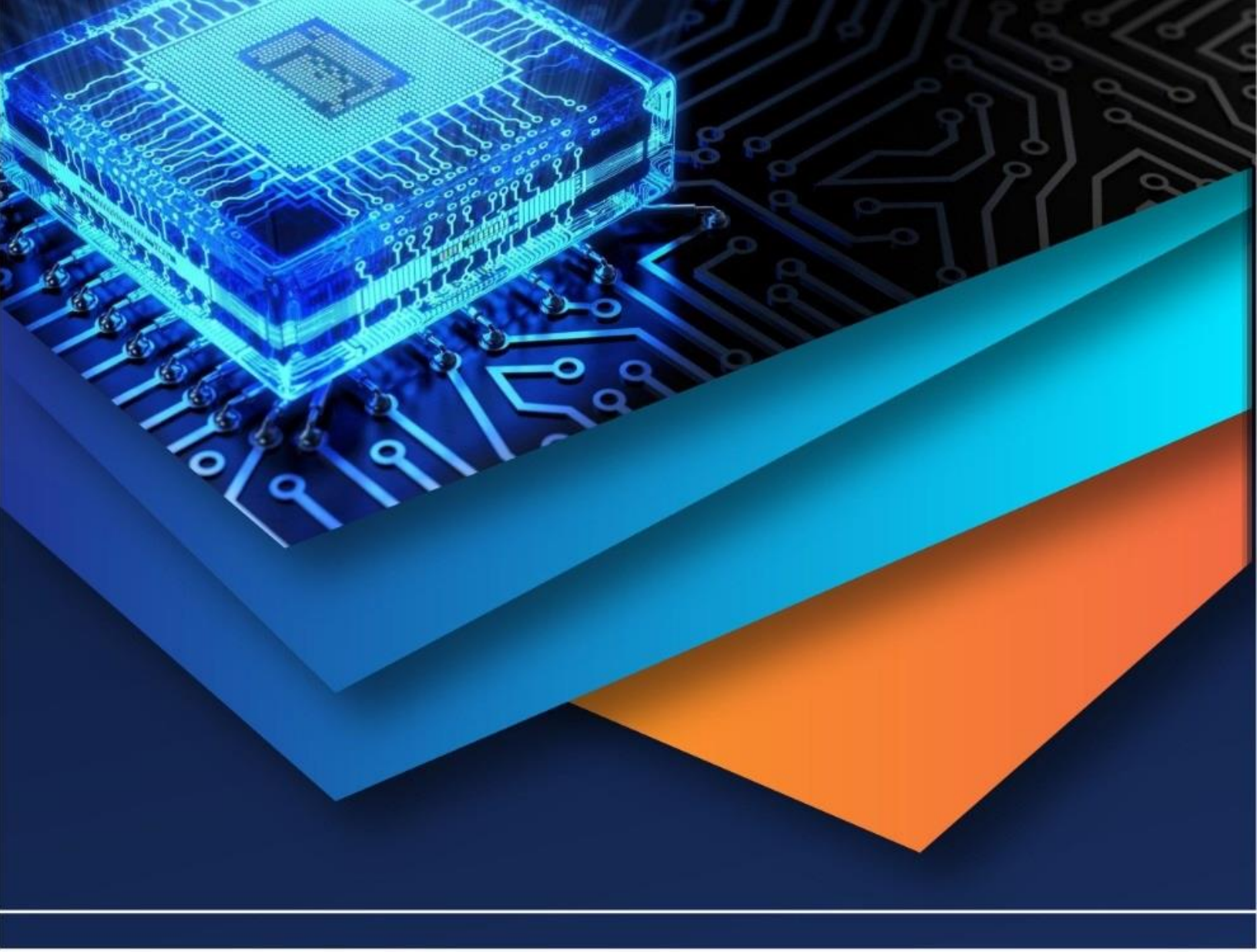
activity. These extracted features are analyzed using machine learning algorithms to estimate blood glucose concentration and predict blood group classification. Among the evaluated models, the Gradient Boosting Regressor achieved the best overall performance with a Mean Absolute Error (MAE) of 14.64 mg/dL, Root Mean Square Error (RMSE) of 19.23 mg/dL, and coefficient of determination (R^2) of 0.7897.

Experimental implementation confirmed successful finger detection, stable PPG signal acquisition, feature extraction, wireless communication with the Flask REST API server, and real-time OLED visualization of predicted results. The implementation of an offline fallback prediction model on the ESP32 further improves system reliability and operational continuity during network unavailability.The research highlights the growing potential of combining photoplethysmography and machine learning for future non-invasive healthcare monitoring systems. The proposed prototype offers advantages such as portability, user comfort, low hardware cost, and real-time analysis capability compared with conventional invasive diagnostic methods.

However, the current system is based on synthetic training data and requires further clinical validation using real patient datasets. Factors such as motion artifacts, environmental noise, skin variations, and sensor positioning may also affect prediction accuracy. Therefore, the developed system should be considered solely as a research prototype and not as a medically certified diagnostic device. Future improvements may include advanced deep learning techniques, wearable integration, cloud-based monitoring, mobile application support, and large-scale clinical testing for enhanced accuracy and practical healthcare deployment.

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