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Design and development of an Arduino-based oxygen saturation, heart rate variability, and blood glucose measurement device

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ABSTRACT

This study presents the design and development of an Arduino-based device for measuring oxygen saturation, heart rate variability (HRV), and blood glucose levels. The primary goal is to create an affordable, portable, and accurate health monitoring solution suitable for home health care and remote medical services. The device integrates a pulse oximeter sensor to measure oxygen saturation and heart rate, an electrocardiogram (ECG) sensor for capturing HRV data, and a non-invasive sensor for regular blood glucose monitoring, all managed by an Arduino microcontroller. Data collected by the sensors is processed and displayed on a user-friendly interface, enabling real-time tracking of health metrics. The device's performance was rigorously tested and validated against standard medical equipment, demonstrating comparable accuracy in measuring the targeted health parameters. This innovative solution aims to enhance personal health monitoring, reduce the burden on healthcare systems, and promote early detection and better management of health conditions. The affordability and ease of use make this device accessible to a wider population, potentially improving health outcomes. Future developments will focus on refining sensor accuracy and expanding the device's capabilities to monitor additional health metrics.

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1. INTRODUCTION

The rapid advancement in portable medical devices has significantly transformed the landscape of health monitoring, providing individuals and healthcare providers with enhanced tools for continuous and real-time health assessment [1]. Monitoring vital health parameters such as oxygen saturation, heart rate variability (HRV), and blood glucose levels is crucial for managing chronic conditions and ensuring overall well-being [2]. Oxygen saturation levels indicate the efficiency of oxygen transport in the bloodstream, a vital metric for assessing respiratory and cardiovascular health [3]. HRV reflects the variation in time intervals between heartbeats, serving as a significant marker for autonomic nervous system function and cardiovascular health [4]. Blood glucose monitoring is essential for managing diabetes, a condition affecting millions worldwide [5]. Traditional methods of monitoring these parameters often involve multiple devices, making the process cumbersome and less efficient, especially for continuous monitoring outside clinical settings [6]. Recent technological advancements, particularly in microcontroller platforms like Arduino, have paved the way for innovative solutions that integrate these monitoring capabilities into a single, portable, and cost-effective device [7]. Arduino offers a versatile, low-cost, and user-friendly platform that can seamlessly integrate various sensors and process data in real-time [8]. This flexibility makes it an ideal choice for developing comprehensive health monitoring systems that are both accessible and reliable [9]. By leveraging Arduino's capabilities, it is possible to design a device that not only provides accurate readings of oxygen saturation, HRV, and blood glucose levels but also enhances the convenience and accessibility of health monitoring, particularly in remote and resource-limited settings [10].

The development of an Arduino-based device for monitoring oxygen saturation, HRV, and blood glucose levels addresses several critical needs in modern healthcare [11]. Firstly, it empowers individuals to take a proactive role in managing their health by providing real-time feedback and tracking health metrics over time [12]. This is especially important for patients with chronic conditions such as chronic obstructive pulmonary disease (COPD), cardiovascular diseases, and diabetes, where regular monitoring can lead to better disease management and improved health outcomes [13]. Secondly, in remote or resource-limited settings, access to healthcare facilities and regular medical check-ups can be challenging. A portable monitoring device can bridge this gap, offering a viable solution for continuous health monitoring and timely medical intervention, thereby improving healthcare delivery and reducing the burden on healthcare facilities [14]. The relevance of such a device has been further highlighted by the COVID-19 pandemic, which underscored the importance of remote health monitoring solutions [15]. The need to minimize hospital visits to reduce the risk of virus transmission has accelerated the adoption of telemedicine and remote patient monitoring [16]. Devices capable of providing reliable and continuous monitoring of vital signs are now more crucial than ever [17]. The proposed Arduino-based device aligns perfectly with this need, offering a comprehensive and accessible tool for both patients and healthcare providers [18]. By integrating multiple health monitoring functions into a single device, the study aims to enhance usability, reduce costs, and improve the overall efficiency of health monitoring [19].

The primary objective of this study is to design and develop an Arduino-based device that accurately measures oxygen saturation, HRV, and blood glucose levels. The goal is to create an affordable, portable, and user-friendly health monitoring solution that can be widely used, including in remote and underserved areas. The study involves several key phases: selecting and integrating appropriate sensors, developing the necessary software for data processing and display, and validating the device's accuracy and reliability through rigorous testing. By achieving these objectives, the study seeks to provide a viable solution for continuous health monitoring, thereby enhancing individual health management and supporting healthcare systems. The scope of the study encompasses both the technical and practical aspects of device development [20]. On the technical side, the focus is on integrating different sensors with the Arduino microcontroller, ensuring accurate data capture and processing. This involves selecting compatible sensors, developing algorithms for data interpretation, and designing an intuitive user interface. Practically, the study aims to validate the device's performance in both controlled environments and real-world settings, comparing its readings with those obtained from standard medical equipment to ensure reliability. The successful development of this device could revolutionize personal health monitoring, offering significant benefits for individual health management and broader healthcare systems.

2. METHOD

The design and development of the Arduino-based device for measuring oxygen saturation, HRV, and blood glucose levels involved a systematic approach to hardware and software integration. Initially, suitable sensors were selected for each parameter: a pulse oximeter sensor (MAX30102) for oxygen saturation and heart rate, an electrocardiogram sensor (AD8232) for HRV, and a non-invasive glucose sensor. The Arduino microcontroller served as the central processing unit due to its versatility, affordability, and ease of programming. Each sensor was interfaced with the Arduino using appropriate libraries and communication protocols (ESP32) to ensure accurate data acquisition as seen in Figure 1. The development process began with the hardware setup, where sensors were connected to the Arduino board, ensuring proper voltage levels and secure connections to avoid signal interference. After establishing the hardware configuration, we focused on software development. Custom algorithms were developed to process the raw data from each sensor. For the pulse oximeter, algorithms were designed to calculate oxygen saturation (SpO_2) and heart rate based on the photoplethysmographic signals [21]. For the electrocardiogram (ECG) sensor, HRV was determined by analyzing the time intervals between R-peaks in the ECG waveform. The non-invasive glucose sensor required calibration and signal processing to correlate sensor readings with blood glucose levels accurately. The processed data were then displayed on an LCD screen or transmitted wirelessly to a mobile application for real-time monitoring.

To validate the accuracy and reliability of the developed device, a series of tests were conducted in both controlled laboratory settings and real-world environments. The device's readings for oxygen saturation, HRV, and blood glucose levels were compared against standard medical equipment, such as clinical pulse oximeters, professional ECG machines, and blood glucose meters. Initially, a small cohort of volunteers was selected for controlled testing [22]. These volunteers underwent simultaneous measurements using the Arduino-based device and standard medical equipment to gather comparative data. Statistical analysis, including calculating correlation coefficients and Bland-Altman plots, was performed to assess the agreement between the device readings and the reference equipment [23]. Following successful laboratory validation, the device was tested in real-world scenarios to evaluate its performance in various conditions, including different levels of physical activity, ambient light conditions, and temperature variations. The real-world testing phase involved a more diverse group of participants to ensure the device's robustness across different demographics and usage scenarios [24]. User feedback was also collected to assess the device's usability and comfort. Any discrepancies or performance issues identified during testing were addressed through iterative improvements in both hardware and software.

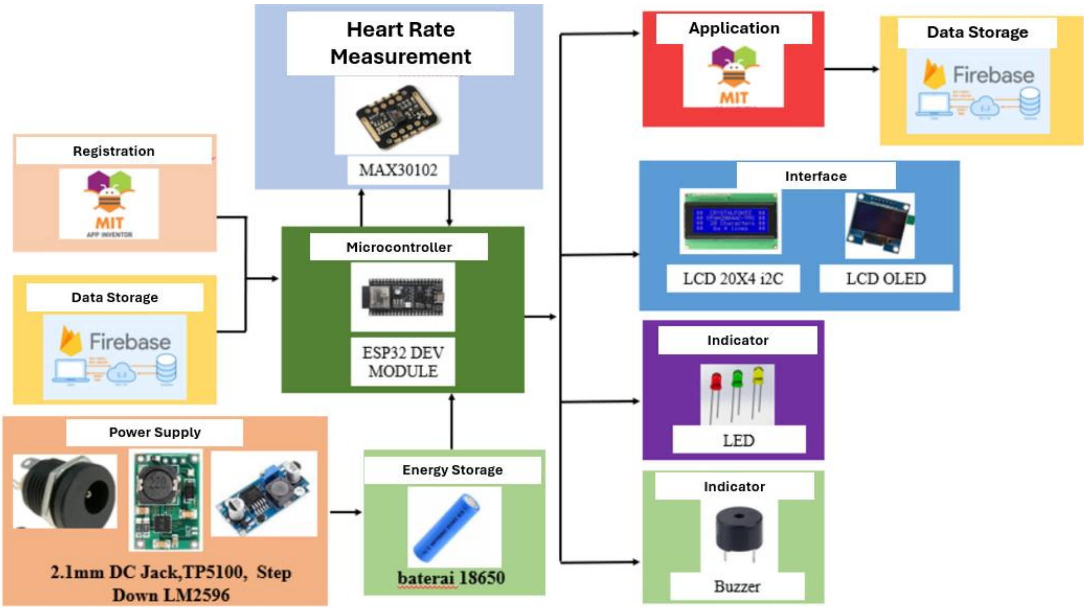

Figure 1. Schematic design of an Arduino-based heart rate variability and blood sugar level oxygen saturation device

3. RESULTS AND DISCUSSION

Development of an Arduino-based pulse oximeter to measure oxygen saturation SpO_2, one of the key components is an emitting diode (LED) and photodiode. The working principle of these two components is very important because they are responsible for measuring the absorbance of light by hemoglobin in the blood, which changes along with the amount of oxygen bound by hemoglobin. The emitting diode functions as the light source in the pulse oximeter. Typically, these diodes use red or infrared light, because these two types of light can penetrate body tissue better than other light. In pulse oximeter applications, the emitting diode will produce light that is emitted through the surface of the skin, usually on the finger or other end of the patient [25]. The light emitted will then penetrate the tissue and be absorbed by hemoglobin in the blood. Photodiodes, on the other hand, function as detectors to measure the light absorbed by hemoglobin. The photodiode is positioned next to the emitting diode so that the light received by the photodiode mostly comes from the light emitted by the emitting diode and has passed through body tissue as seen in Figure 2. Hemoglobin which contains oxygen and does not contain oxygen has different light absorbance, especially in a certain wavelength of light [26]. The photodiode measures the intensity of the light received and produces an electrical signal based on the amount of light that makes it through the finger or body part being measured [27].

The main working principle of a pulse oximeter is to utilize differences in light absorbance by hemoglobin depending on whether the hemoglobin binds oxygen or not. When oxygen is bound to hemoglobin, there will be a change in the absorbance of the light emitted by the emitting diode. In general, oxyhemoglobin has a lower absorbance of red or infrared light compared to deoxyhemoglobin (hemoglobin that does not bind oxygen). A complex mathematical algorithm is used to calculate the oxygen saturation percentage SpO_2 based on the difference in light intensity received by the photodiode. The data obtained from the photodiode is processed by the Arduino microcontroller using an empirical formula or mathematical model that has been previously calibrated [28]. This processing involves steps to reduce noise and artifacts that can affect the accuracy of SpO_2 measurements, such as body movement or incoming environmental light as seen in Figure 3. The accuracy of SpO_2 measurements is highly dependent on the quality of the signal received by the photodiode. Therefore, proper arrangement of emitting diodes and photodiodes, as well as selection of appropriate light wavelengths, is essential to ensure accurate results. In addition, routine calibration and maintenance of hardware and software are also required to maintain equipment reliability over the long term. In the context of the development of Arduino-based medical devices, the integration of emitting diodes and photodiodes with microcontrollers allows the creation of cheap, portable, and reliable pulse oximeters [29]. This provides the potential to increase the accessibility of healthcare in a variety of settings, both in hospitals and for personal use [30]. Thus, the development and in-depth understanding of the working principles of emitting diodes and photodiodes in pulse oximeters is the key to achieving an effective tool for accurate and reliable SpO_2 measurements.

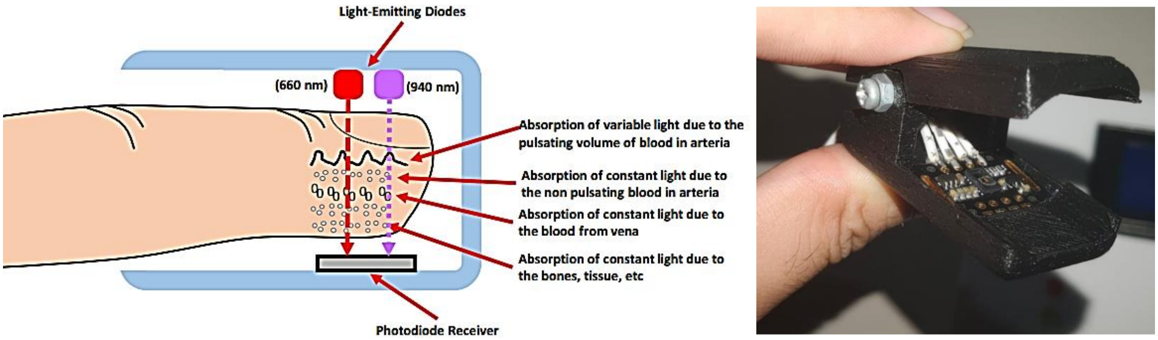

Figure 2. Schematic of the working principle of emitting diodes and photodiodes in a pulse oximeter

In the software design stage, Arduino programming was implemented, and an application was developed using MIT App Inventor, which is connected to Firebase for data storage as can be seen in Figure 3. The software design has successfully integrated all system components, allowing the device to function according to the design concept. In the hardware design stage, an acrylic box was constructed to house various components, including the LCD 20×4 I2C, LED, buzzer, ESP32, battery, Step Down LM2596, TP5100 charger module, and MAX30102 sensor. The hardware design ensures proper organization and placement of components within the device. Once the software and hardware design stages were completed, the device underwent testing to verify its performance according to the design concept and objectives. The device employs the reflectance photoplethysmography (PPG) method using the MAX30102 sensor to obtain data for oxygen saturation, heart rate variability, and blood glucose levels [31]. The measured data is then transmitted to the connected application via ESP32 and stored in Firebase, enabling data storage and retrieval at any time [32]. The obtained data from the device is compared with readings from conventional oximeters and easy-touch devices to validate the accuracy and reliability of the device.

The software on this tool is designed to process raw data received from integrated sensors to produce values that are understandable and clinically useful. First of all, the software must be able to accurately retrieve data from the sensors installed on the Arduino. These sensors, such as pulse oximeters to measure SpO_2 and heart rate sensors to measure HRV, produce analog or digital signals that need to be converted into a more structured and analyzable form. The software will convert this data into relevant units, such as SpO_2 percentage for oxygen availability in the blood, HRV index to measure heart rate variations, and glucose levels in mg/dL or mmol/L. Second, the software is also responsible for presenting data visually through an intuitive user interface. This interface allows users to monitor and understand measurement results easily. Information such as graphs of SpO_2 and HRV values over a certain period can be displayed, which helps users track their health patterns over time [33]. In addition, the software can also have features to store measurement data in an easily accessible format, either for daily monitoring purposes or for long-term analysis by health professionals. Software development also involves implementing complex algorithms to calculate health values based on the data obtained. For example, calculating HRV values involves analysis of the periods between recorded heartbeats. This algorithm must be optimized to obtain accurate and reliable results, as HRV is an important indicator of the health of the heart and autonomic nervous system. In addition, in measuring glucose levels, the software must be able to calculate the correct value based on the sensor's response to glucose in the blood [34]. Software validity and reliability are also important aspects to consider. Development must ensure that every calculation and data processing is carried out correctly and can be repeated with consistent results. Software testing is carried out thoroughly to ensure that there are no bugs or errors that could affect the accuracy or reliability of the measurement results [35]. Overall, software development in this measurement tool plays an important role in ensuring that the tool can make a significant contribution to the use of technology for independent health [36]. With the right combination of well-designed hardware and sophisticated software, it is hoped that this tool can help in monitoring health more accurately and effectively, as well as provide meaningful solutions in the prevention and management of chronic diseases such as diabetes and respiratory disorders.

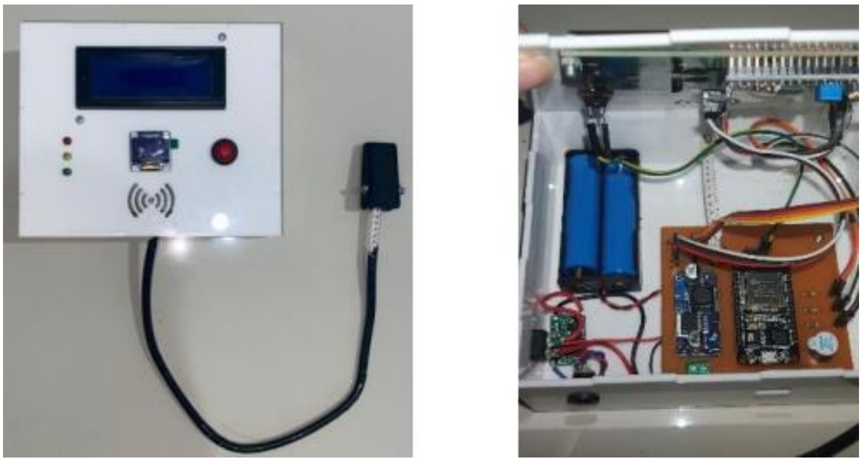

Figure 3. Prototype automatic measurement

In the development of an Arduino-based measurement tool that includes the function of measuring oxygen saturation, HRV, and blood sugar levels, testing of ECG signals is carried out in two different body positions: sitting and standing. This test aims to evaluate the consistency and accuracy of the device in recording ECG signals under varying postural conditions, reflecting real-use situations in clinical and non-clinical environments. The test results show that the Arduino-based measuring device can record ECG signals well in both positions. In the sitting position, the resulting ECG wave shows a clear morphology of P waves, QRS complexes, and T waves, with little noise interference which can be minimized through digital filters [37]. The R-R intervals calculated from these ECG signals are stable and consistent, allowing accurate HRV analysis. When subjects transitioned to a standing position, there was an increase in heart rate variability noted, a normal physiological response to changes in posture. The ECG signal in the standing position still shows the same wave components with sufficient clarity, although there is a slight increase in noise and more prominent motion artifacts [38]. Good signal processing algorithms help in reducing these artifacts, ensuring that the resulting data remains valid and usable for further analysis.

Further discussion regarding the differences in ECG signals in the sitting and standing positions includes clinical and technical implications. From a clinical point of view, the device's ability to reliably record ECG signals in a variety of body positions demonstrates its reliability and flexibility for daily health monitoring. This is important for users who may need to monitor their heart condition during various daily activities. Figure 4 shows that changes in HRV recorded when subjects transitioned from a sitting to a standing position provide additional information about the response of the autonomic nervous system to postural changes, which can be an important indicator in the diagnosis and monitoring of cardiovascular conditions [39]. Technically, these results confirm that this Arduino-based device, with its sensor design, can handle the challenges associated with changes in body position that usually give rise to movement artifacts. The implementation of digital filters and effective signal processing algorithms ensures that noise and movement artifacts are minimized so that data quality remains high. Validation carried out by comparing the measurement results of this tool with standard ECG devices showed a strong correlation, confirming that this tool has a sufficient level of accuracy for clinical use [40]. Thus, the integration of the ECG function in this measurement tool adds significant value, enabling more comprehensive and accurate health monitoring in a variety of postural situations, increasing the potential of this tool as an integrated and practical health monitoring solution.

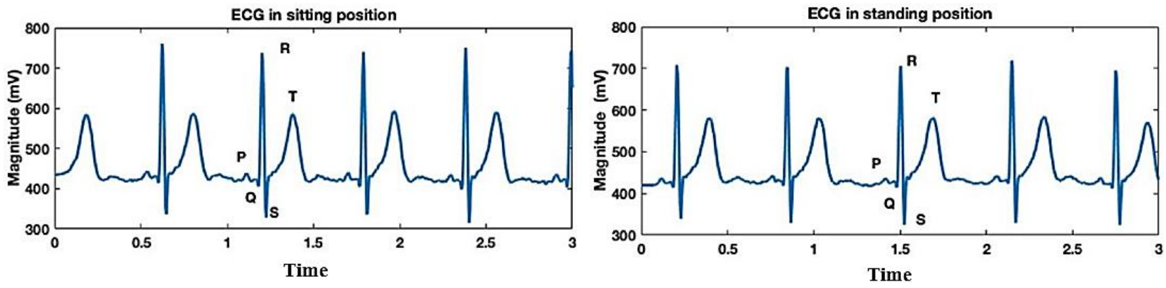

Figure 4. ECG in different body conditions

Evaluation of tool performance and measurement validity in the development of Arduino-based measurement tools for SpO_2, HRV, and blood glucose levels is a crucial stage in ensuring the reliability and accuracy of these tools in clinical and diagnostic applications. Testing is carried out thoroughly to verify that the tool is capable of providing consistent and reliable results under various conditions of use. First, evaluation of device performance involves laboratory testing to test the sensor's response to controlled variations in environmental conditions. This test aims to evaluate the sensitivity, specificity and accuracy of device measurements under controlled conditions such as changes in temperature and humidity. For example, SpO_2 sensors must be responsive to changes in oxygen saturation over varying degrees, while HRV sensors must be able to accurately measure heart rate variability without being affected by external interference [41]. Next, the validity of the measurements was evaluated through clinical testing on human subjects. This test is carried out to compare the results of device measurements with values obtained from standard methods or medical devices whose validity has been proven [42]. Test subjects involved in clinical testing represent populations that may use the device, such as patients with certain medical conditions or healthy individuals as controls. The data obtained from this test is analyzed to determine the level of concordance between the tool measurement results and the comparison method, as well as to verify the tool's reliability in practical applications. The results of the evaluation of the tool's performance and the validity of these measurements are important to confirm that the developed measuring tool can be used with confidence in healthcare applications [43]. By ensuring that the tool provides consistent and accurate results, users can rely on the information provided for informed clinical decision-making. The validity of the measurements also guarantees that the tool can make a meaningful contribution to the self-monitoring of health and management of chronic diseases, such as diabetes and cardiovascular disease, where continuous monitoring of health parameters is key to effective prevention and management.

4. CONCLUSION

In summary, the development of an Arduino-based device for measuring oxygen saturation, HRV, and blood sugar levels has been successfully carried out with satisfactory results. The device demonstrates the ability to measure important health parameters with high accuracy, utilizing modern sensor technology integrated with the flexible and cost-effective Arduino platform. Electrochemical testing of the glucose sensor showed linear and accurate results in the relevant concentration range, while the ECG module used managed to record ECG signals clearly in both sitting and standing positions. HRV analysis performed based on ECG data provides valuable information about heart health conditions, demonstrating the potential of this tool for use in real-time monitoring of cardiovascular conditions. Overall, this tool offers an effective and practical solution for health monitoring in a variety of conditions and environments, both clinical and non-clinical. The integration of various measurement functions in one device not only makes it easier for users to monitor various aspects of their health simultaneously but also provides comprehensive and integrated data that can be used for more in-depth analysis. Given the relatively low cost and ease of use offered by the Arduino platform, this tool has great potential for widespread adoption, especially in the context of home self-health monitoring. This innovation can contribute significantly to improving the quality of life for patients with chronic conditions, such as diabetes and cardiovascular disease, through more accurate, efficient, and user-friendly monitoring.

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