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Development of a low-cost medical pulse oximetry system

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Abstract
In recent medical practice, there is a need to continuously monitor oxygen saturation of hemoglobin in artery blood. The use of pulse oximetry for oxygen therapy and treatment of diseases associated with respiratory or cardiovascular systems is attracting growing attention. Despite the immense importance of wearable technology such as pulse oximetry, there is dearth of such devices in Sub-Sahara African countries. Thus, this study was aimed to develop a low-cost pulse oximetry system for monitoring oxygen saturation of hemoglobin in hospital patients. The circuit diagram for the intended pulse oximetry system was first designed and thereafter Printed Circuit Board (PCB) was produced. This was followed by printing on PCB, etching and soldering. Different components were then assembled to fabricate the oximetry system. Finally, performance testing of the developed system was done. Once the data is processed, the microcontroller unit of the oximetry system displays the output to the screen. It was observed that a waveform indicating pulsatile flow in the arteries was used for determining heart rate, oxygen saturation, and temperature. When the reading of any of the targeted parameters is above a threshold value, which indicates high readings, the buzzer was implemented to beep for alertness and immediate response. In the present work, development of a low-cost medical pulse oximetry system for use in Nigeria and other Sub-Sahara African countries has been demonstrated. While limitations such as privacy concerns require immediate attention, there is no doubt that wearable technologies are not only capable of working as an early warning system, but also as life-saving devices.

Keywords: *Pulse oximetry, Oxygen, Therapy, Microcontroller and Low-cost*

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I. Introduction

The human body is a biological machine maintained by interdependent body systems and organized biochemical reactions (Cherif et al, 2012**).** Oxygen supply is critical to the existence of the biological machine. It is considered as the most commonly used drug in emergency medicine and treatment of hypoxaemia (Nakane, 2020). It is often applied as a therapeutic agent for treatment of illnesses involving respiratory systems and severely ill patients (Alfadda and Sallam, 2012; Tretter et al, 2020; Jha and Gaur, 2022). Lack of oxygen, commonly termed as hypoxia, is frequently encountered in different disease states and is detrimental to human life (Tretter et al, 2020). In emergencies such as the one created by the flare of Covid-19, oxygen consumption has increased tremendously (Jha and Gaur, 2022).Oxygen therapy is an essential medicine and core component of effective hospital systems (Graham et al, 2020).

Many works on how dearth of oxygen supply promotes diseases such as COVID-19 have been reported. In the work of Bularga (2022)., the prevalence and outcomes of different factors associated with oxygen supply-demand imbalance among patients with type 2 myocardial infarction was studied. Analysis of a randomized clinical trial, mortality after type 2 myocardial infarction was attributed to the underlying oxygen supply-demand imbalance. In 2019, a novel Coronavirus Disease 2019 (COVID-19) sometime referred to as Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) emerged in Wuhan, China (Brosnahan et al., 2020), and has caused a substantial increase in hospitalizations worldwide (Islam et al., 2020, Wiersinga et al, 2020 and Toner, 2021). Many hospitals in low- and middle-income countries lack reliable oxygen access—a deficiency exacerbated by emergence of COVID-19 (Graham et al, 2020 and Toner, 2021). Oxygen has been found to be a life-saving therapy for patients with COVID-19 (Calligaro et al., 2020andHvarfne et al, 2022).The world health organization estimated the average flow-rate of oxygen to severe COVID-19-patients to be 10 litres/min. (Hvarfne et al, 2022).Nevertheless, oxygen is a limited resource in many hospitals in low income countries.

Several emerging diseases pose a critical threat to global health security due to increased global movement of goods and people. For human health, the circulatory system is extremely important because it transports blood, oxygen and other materials to the different organs of the body (Hazra et al, 2017). Furthermore, the heart plays the most crucial role in the circulatory system. If the heart does not function properly, then it will lead to serious health conditions including death. Therefore, there is a growing emergence of new methods for predicting different pathological diseases (Xiu et al., 2022). Hazra et al (2017) in their review described how various machine learning techniques were used for heart disease diagnosis. Suitable application of Medical Diagnosis Expert System (MDES) has been used to manage diseases in developing countries (Nkuma-Udah et al., 2018).The authors reported its use by clinicians for disease detection. In the work of Tison et al. (2019), an automated and interpretable patient ECG profile was explored for detection, tracking and discovery of diseases. Other interesting disease detection studies have also been reported (Mazumder et al, 2013, Huang and Xie, 2014; Scherf et al., 2018 and Nashif et al., 2018).

Sequel to the foregoing, there is a need for cost-effective technologies for management of diseases and thus reducing morbidity and mortality in the developing countries. The use of new technology of pulse oximetry for treatment of infections or diseases associated with respiratory or cardiovascular systems is attracting growing attention. This was well corroborated in Hundessa and Hakkins(2022),Reddy et al. (2023), Rojas and Mosquerra (2024), Sarraf (2024a) and Sarraf (2024b)that emphasized critical role of pulse oximetry for measurement of blood oxygen saturation , monitoring of chronic diseases and pulse rate for the needed clinical intervention. Improving access to oxygen and pulse oximetry has demonstrated a reduction in mortality from childhood pneumonia by up to 35% in high-burden child pneumonia settings. In addition to its use in treating acute respiratory illness, oxygen treatment is required for the optimal management of many other conditions in adults and children, and is essential for safe surgery, anaesthesia and obstetric care (Duke et al, 2010). Pulse oximetry is explored in modern medicine to continuously and transcutaneously monitor the functional oxygen saturation of hemoglobin in artery blood (Chan et al., 2013). It plays an essential role in early detection of hypoxaemia and in guiding oxygen therapy (Herbert and Wilson, 2012).In Luks and Swenson (2020), the use of pulse oximetry for monitoring patients with COVID-19 has been demonstrated. In a study carried out by Graham et al. (2022), an attempt was made to demonstrate the use of pulse oximetry for some Nigerian children who are pneumonia patients. Their study was carried out with the aim of examining the impact of oximetry on improving quality of care for children who are pneumonia patients. The findings obtained by the authors yielded recommendation on establishment of stabilisation rooms for short-term oxygen delivery for children with hypoxaemia prior to transfer to hospital. It was also reasoned that such stabilisation rooms could serve as a suitable support to short-term COVID-19 and long-term paediatric pneumonia patients.

Although some attempts have been made on design and construction of pulse oximetry (Gölcük et al, 2016; Omotosho et al., 2017; Kramer et al., 2017 and Naeem et al., 2021). There are extremely limited pulse oximetry devices in Sub-Saharan Africa countries. Therefore, the objective of this study was to develop a low-cost pulse oximetry system for monitoring oxygen saturation of hemoglobin in hospital patients.

II. Materials and Methods

The seven major components/modules/system for circuit design for the pulse oximetry system are finger sensor and analogue processing; Microcontroller system; Temperature measurement module; GSM module; Real time clock module; Power supply circuit and Critical temperature circuit. The complete circuit diagram used for the design of pulse oximetry system is described in Figure 1.

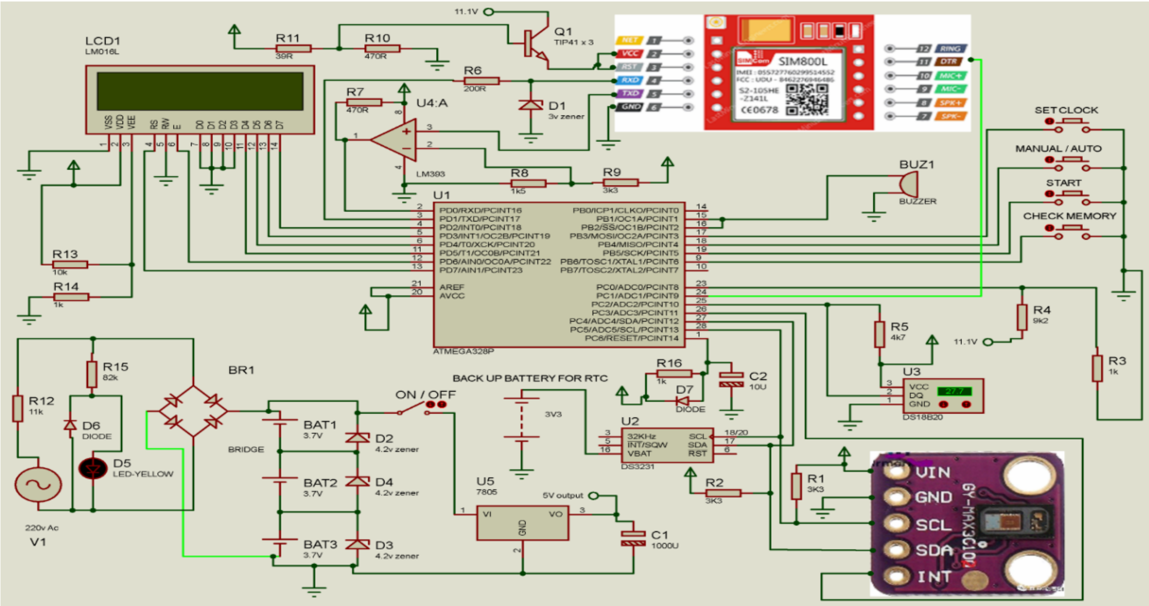

Figure 1: Circuit diagram pulse oximetry system

The construction of a pulse oximetry system was implemented in five stages described as follows:

i. Design of Printed Circuit Board (PCB)
ii. Software design, printing and etching on PCB
iii. Soldering on the PCB
iv. Components assembling and construction
v. Performance testing
vi. Packaging / Casing

a. Design of Printed Circuit Board (PCB)

A Printed Circuit Board (PCB) mechanically supports and electrically connects electronic components using conductive tracks, pads and other features etched from copper sheets laminated onto a non-conductive substrate. Components such as capacitors, resistors or active devices, were soldered on the PCB. The PCBs were designed with dedicated layout software using EXPRESS PCB. Proteus 8.9 software was used for circuit design and simulation. Assembly language was used to program the microcontroller- ATmega 328.

b. Software Design, Printing and Etching on PCB

The software used in designing this system was EXPRESS PCB. The software was used in routing components together, after the completion of this was printing of the design on a glossy paper. The printed design went through different processes from the application of chemical –ACETONE used to imprint the printed design on glossy paper onto the PCB. This was followed by etching with the use of Iron Carbonate (Fe_2CO_3) to etch away-unwanted parts of the design leaving the ink of the printed part. These processes were completed by drilling of the PCB for components to be arranged on it before proceeding to the next stage.

c. Soldering on a Printed Circuit Board (PCB).

The PCB has lines and pads that connect various points together. It allows signals and power to be routed between physical devices. Solder was the metal used for electrical connections between the surface of the PCB and the electronic components. Solder also serves as a strong mechanical adhesive. In order to ensure good contacts and to avoid dry joints during soldering, all the components soldered were first cleaned by scraping their legs with sandpaper until the copper became visible. The copper tracks on the board were cleaned in a similar manner. This made soldering much easier as molten solder flows freely over such surfaces. Heat was applied at the right temperature and for sufficient time to ensure that a good joint was made. After soldering the circuit components, electrical contact was tested by setting a multimeter to continuity test mode. One terminal of the meter was placed on the soldered joint, while the other leg was placed on the copper track to which it was soldered. If the joint was well made, the multimeter emitted a beep sound and if not, it indicated an open connection.

III. Results and Discussion

The outcome of fabrication of different components and their subsequent assembly are presented here. Figure 2 shows a soldered PCB board consisting of various sections. The soldered panel with all the components that make up the entire pulse oximetry system is described in Figure 3. Figure 4 describes the buttons panel for starting the operation of the pulse oximetry system. The buttons are also used to set day, year, time in hours, minutes and seconds on the system. Figure 5 shows casing used for the constructed system. Figure 6 illustrates fixed and tested components mounted inside the casing. The GSM module SIM 400 used in the design and pulse oximetry system are shown in Figure 7 and Figure 8, respectively. The real time clock module, 3-Dimensional designed finger holder for pulse oximetry test and the completed design mounted in the casing are illustrated in Figure 9, Figure 10 and Figure 11, respectively. The temperature sensor attached to the design unit was shown in Figure 12.

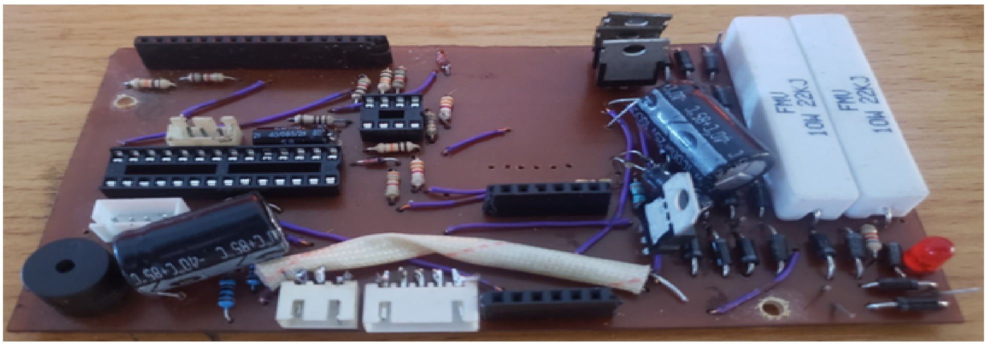

Figure 2: Soldered PCB board consisting of various sections

Figure 3: Soldered panel with all the components in pulse oximetry system

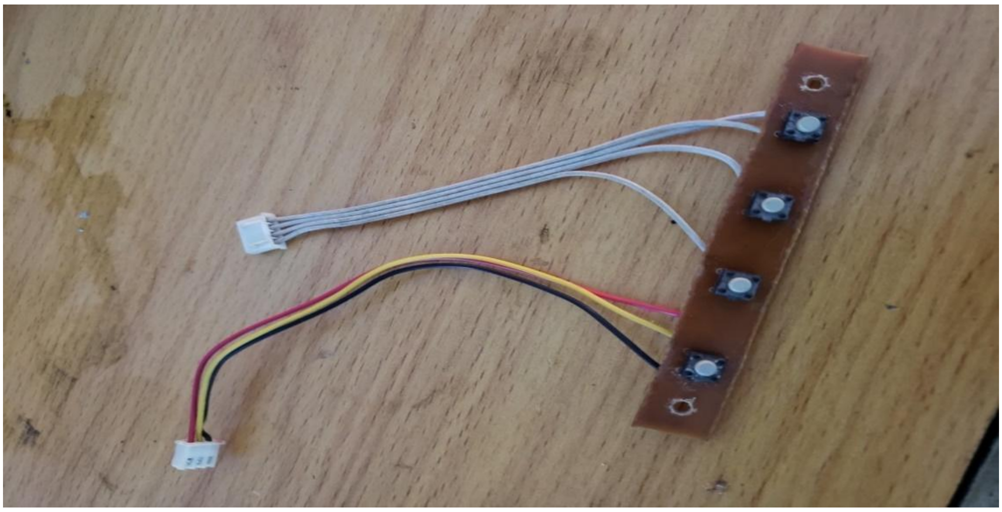
Figure 4: Buttons panel for starting the operation of pulse oximetry system,


Figure 5: Casing for the pulse oximetry system.

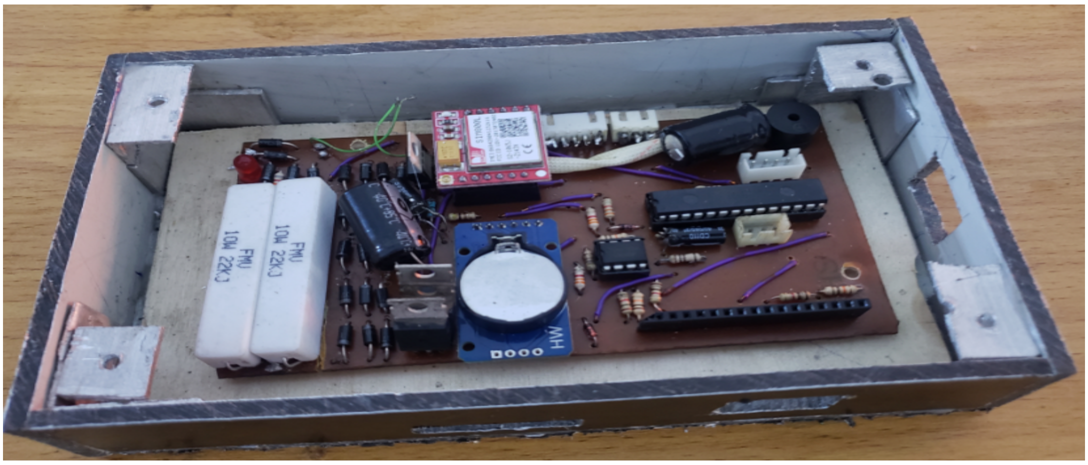
Figure 6: Fixed and tested components mounted inside the casing

Figure 7: GSM module SIM 400 used in the design

Figure 8: Pulse oximetry module

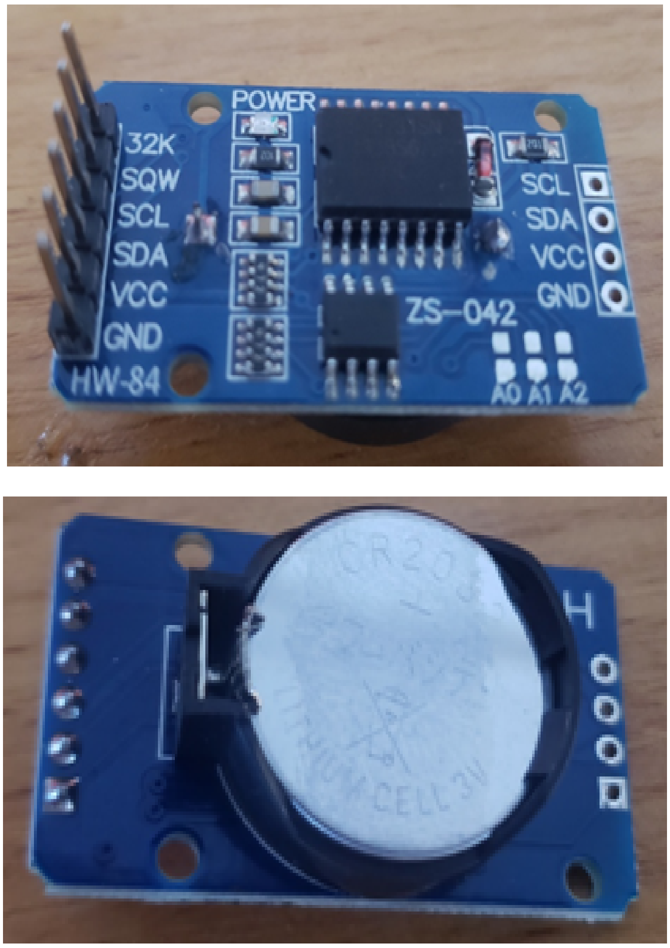

Figure 9: The real time clock module

Figure 10: 3-Dimensional designed finger holder for pulse oximetry test

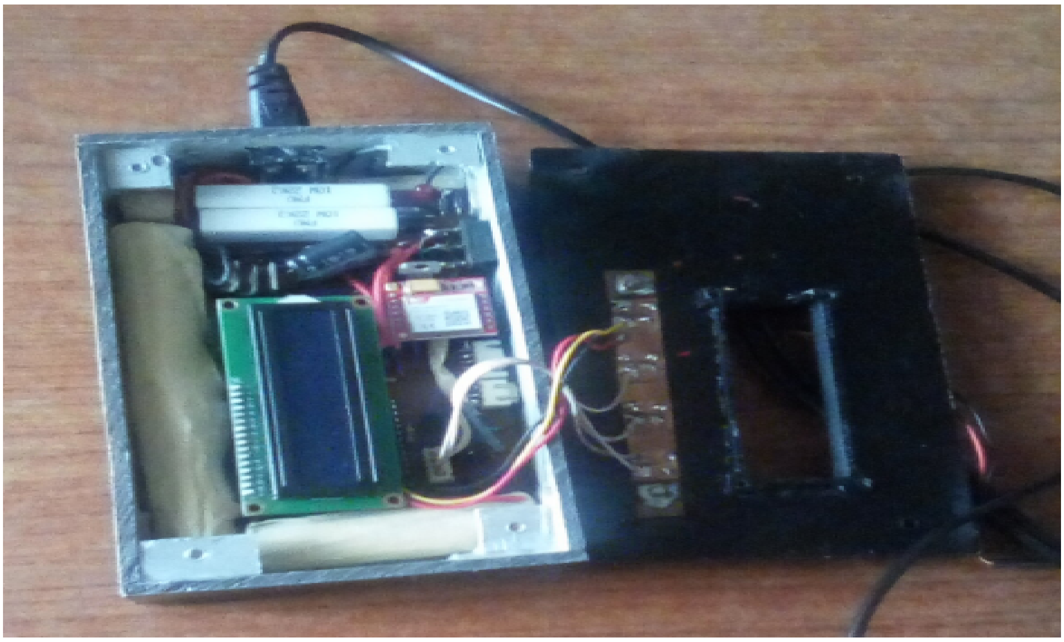

Figure 11: Pulse oximetry system prototype mounted in the casing

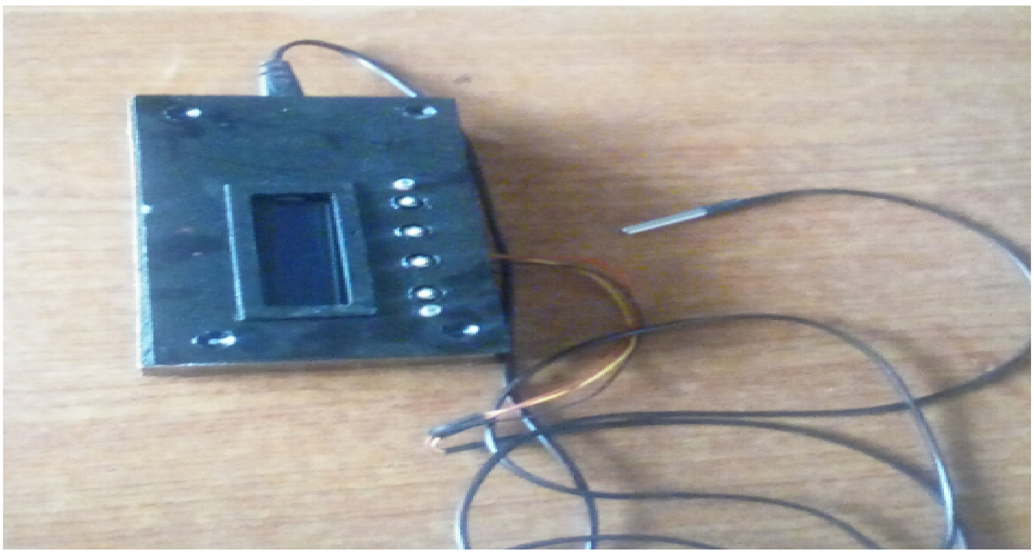

Figure 12: Temperature sensor attached to the Pulse oximetry system

Testing of components is important during construction to ensure that the works compiled together are perfect with their specifications. Testing is also essential during operation and after the completion of the construction to determine the longevity of the inverter in order to detect common faults that may arise. These are the component and system testing needed for any successful project.

3.1 Component testing
Every component was tested singly to ensure that each is in good condition before assembling on the board. The major test carried out on these components is continuity testing done with the use of a multimeter. The test made on transistors was used to test each terminal of a transistor. Polarity testing was also performed on some components like diodes, capacitors and transistors.

3.2 System testing
This involves the testing of the entire circuit and thus, examining it for errors like short-circuits, Lead flux, joining unwanted links. Proper insertion of IC pin layout and also checking if ICs of these pin numbers are slotted in their proper base. After checking, cross check again before powering the system.

It was observed that components used for the construction are not predominantly static, electronic data books played a major role in identifying other available components in the absence of one. The following observations were made during the testing:

i. The pulse oximetry device consists of three key components— device housing, circuitry, and microcontroller. The device housing encloses the unit and prevents it from becoming damaged by the external environment. The microcontroller atmega 328 computed oxygen saturation, heart rate monitor, body temperature through a set of programs loaded into it.
ii. The device housing consists of a contoured plastic body that the user holds and a temperature sensor probe that protrudes from the device and which is placed against the skin. The device exterior also contains a single-pole-single-throw power switch, an ON and OFF button to initiate operation. The Liquid Crystal Display (LCD) screen and the protruding probe were placed on opposite faces.
iii. All the activities going on in the pulse oximetry were monitored on the LCD
iv. The real time clock module was able to monitor and record day, month and year, the readings are being taken in hours, minutes and seconds.
v. The recorded values were sent to the health officer or administrator for accuracy in case of high readings as text messages through the inserted SIM
vi. All the activities of the pulse oximetry were displayed on the LCD
vii. The user places the device on the palm of his hand. The button on the top of the device is pressed, and the screen indicates to the user to apply more pressure if the force sensor indicates that insufficient pressure has been applied.
viii. A signal is acquired, while the LCD screen displays a status bar. Once the data is processed, the microcontroller displays the output to the screen. The screen shows the heart rate, oxygen saturation, and temperature (a waveform indicating pulsatile flow in the arteries), when the readings of the parameters get above a set value, which indicate high readings, the buzzer will beep for alertness for immediate response.
ix. However, to ensure patient safety, if the battery's voltage is low, the microcontroller will display an error message that also shows on the LCD as an error message to prompt the user to recharge or change battery in case it is in bad condition.

IV. Conclusions

The goal of this work was to design and implement a working microcontroller based pulse oximetry system. The intended pulse oximetry system was designed and printed on a circuit board. Different components were then assembled to fabricate the oximetry system. A waveform indicating pulsatile flow in the arteries was used for determining heart rate, oxygen saturation, and temperature. The outcomes of this study have shown that the development of a low-cost medical pulse oximetry system for use in Nigeria and other Sub-Sahara African countries is achievable. While limitations such as privacy concerns require immediate attention, there is no doubt that wearable technologies cannot only work as an early warning system but also as life-saving devices. Although wearable technologies such as medical pulse oximetry systems demonstrate tremendous potential in dealing with COVID-19 and other similar infectious diseases, privacy concern is one of the main limitations that hinder its widespread adoption. Notwithstanding, there is no iota of doubt that wearable technologies are not only capable of working as an early warning system, but also as life-saving devices.

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