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Design, Simulation, and Implementation of a Digital Pulse Oxygen Saturation Measurement System Using the Arduino Microcontroller

Muhibul Haque Bhuyan, Md. Refat Sarder

***Abstract*—**If a person can monitor his/her oxygen saturation level intermittently then he/she can identify his/her condition early and thus he/she can seek a doctor's help. This paper reports the design, simulation, and implementation of a low-cost pulse oxygen saturation measurement device based on a reflective photoplethysmography (PPG) system using an integrated circuit sensor as the fundamental component of this health status checking device. The measurement of the physiological parameter is the blood oxygen saturation level (SpO_2) in the peripheral capillary. This work has been implemented using an Arduino Uno R3 microcontroller along with this sensor integrated circuit (IC). The system is designed in the Proteus environment and then simulated to check its performance. After that, the hardware implementation is performed. We used a clipping type optical sensor to sense the arterial oxygen saturation level of blood signal from the fingertips of an individual and then transformed it into the digital data in the microcontroller through its programming its instruction. The designed system was tested by measuring the SpO_2 level for several people of different ages, from 12 to 57 years of age. Besides, the same people were tested using a standard machine purchased from the market. Test results were found very satisfactory as the average percentage of error was very low, 1.59% only.

***Keywords*—**Digital pulse oxygen saturation level, oximeter, measurement, design, simulation, implementation, proteus, Arduino Uno microcontroller.

I. Introduction

THE pandemic of the new coronavirus ailment (COVID-19) started in Wuhan, China in 2019. In the early part of 2020, the COVID-19 disease had been identified in almost every country in the world [1]. The World Health Organization (WHO) issued several technical guidelines to combat the novel coronavirus and also declared it a pandemic [2]. The first coronavirus case was identified in Bangladesh on 8 March 2020 and the first death due to the coronavirus was reported on 18 March 2020, 10 days after reporting the first COVID-19 definite case [3]. However, the current death rate due to coronavirus infection is much less than those the average death rate of the World. The rate can be minimized if people become more careful and even after infection they abide by all the rules and regulations provided by the physicians.

M. H. Bhuyan is with the Department of Electrical and Electronic Engineering (EEE), Southeast University, 251/1 & 252 Tejgaon Industrial cum Commercial Area, Dhaka, Bangladesh. Email: muhibulhb@gmail.com (corresponding author, phone: 88-01815-657346; e-mail: muhibulhb@seu.edu.bd).

M. R. Sarder is with the Department of Electrical and Electronic Engineering (EEE), Southeast University, 251/1 & 252 Tejgaon Industrial cum Commercial Area, Dhaka, Bangladesh (e-mail: 2015000500060@seu.edu.bd).

Engineering and technology have enabled our life-style very comfortable today. In each professional field, we need knowledge of it. The application of knowledge of engineering and technology in medical science has made the tasks of medical professionals very easy. Recent progress of bio-sensors has diminished the size and weight as well as power consumption, and hence there is no problem with wearing the devices all the time. With the arrival of healthcare wearable technology, various types of healthcare wearable monitoring devices are being introduced, and these devices can be used successfully for immediate disease detection by collecting the physiological data, prevention by providing the necessary treatment. Most of these devices can be synchronized with laptops or smartphones where the physiological data can be stored and analyzed through any software. This also helps health professionals to keep track of their patients regularly and on time [4], [5].

Out of several medical data, the oxygen saturation level is the most common to understand the patient's conditions. Oxygen saturation sometimes called the "fifth vital sign" along with the temperature, blood pressure, heart rate, and breathing or respiratory rate of the human body is a parameter that shows how much oxygen is being carried in the blood in comparison to its full capacity. That is, it is a ratio in the percentage of oxygen-carrying hemoglobin to the no-oxygen-carrying hemoglobin in the blood. A person with a good physical condition must have oxygen saturation or SpO_2 level of more than 95% [6]. The value of SpO_2 level less than 95% indicates that the patient may have any respiratory diseases viz. pneumonia or asthma [7]-[9] or may have other systemic inflammatory or infectious disease [10]. To detect such types of diseases at an early stage, a pulse oximeter is a useful device, which can distinguish between severe pneumonia and simple cold or slight infections. Low oxygen saturation can cause serious damage to the internal organs, such as the heart and brain, and needs to be promptly addressed. From these data, the medical professionals diagnose the problems related to the respiration status of the patient. To measure this accurately, the pulse oximeter is very popular. Without the help of this machine, doctors and health professionals are unable to detect the heart-related problems of the human body. However, this detection is very necessary, since the world possesses about an aggregate of 17.65 million individuals who are at a high risk of getting attacked by heart diseases [1].

In light of the above contexts, enormous endeavors have been applied to facilitate the best healthcare services at an affordable expense during the last few decades. With the rapid advancements in engineering and technological fields, it has become feasible to design and develop more efficient, reliable, and affordable biomedical machines and equipment with new additional but important features. This has also made these biomedical machines more user friendly. The prime objective of this work is to propose an automated and low-cost oxygen saturation measurement system to help and support the doctors to monitor their patients' conditions. However, this machine is not still so cheap to the people of under-developed or developing countries. Moreover, doctors and medical staff are not physically available to all required places throughout the country due to the pandemic situation. Therefore, it would be supportive if it is possible to design and then implement a system for the peoples of these countries to monitor their oxygen saturation at an affordable cost from remote places. Biomedical engineers are trying to find a way to address these problems and find a suitable solution to the same. This will certainly decrease their on-site visiting time. Moreover, the Arduino microcontroller is very cheap and readily available in the market and requires fewer efforts for its programming to automate the system. Also, these are used in various biomedical and other similar applications due to the compactness, portability, less power consumption, enhanced battery life, high operating speed, etc. [7]-[10]. This Arduino microcontroller with analog interfacing circuits, sensors, electrodes, amplifiers, samplers, and filters can acquire the very weak signal from the chest and send it to the microcontroller's output port in an appropriate format. Then a set of programming instructions inside the microcontroller can determine the heart rate of the patients being monitored. Therefore, our objectives of this work are to-

i. Design a low-cost SpO_2 measurement system
ii. Use the microcontroller for faster signal processing and several other computation tasks
iii. Simulate the system in the Proteus environment
iv. Analyze the oxygen saturation data

II. Literature Review

In the literature, several types of digital pulse measuring devices were found. Most of the designs were based on microcontroller. One such paper by Laghrouche et al. claimed the design of a low-cost microcontroller and medical sensor node based device for concurrent measurement of the arterial blood's oxygen saturation level and heart rate that can be used by the general people at home easily and safely. Though they claimed it is a low-cost device but the cost analysis and cost comparison are not shown. Measurement data were not compared with that of the standard device. It was also claimed that the device is small-sized and lightweight, has the capability of wireless signal transmission, standardized signal processing, and data processing. However, this is not shown in detail in their paper [11].

Another paper described the implementation of an oxygen meter that connects an oximeter to the smartphone through the headset jack audio interface and verifies the system via a simulator for auto authentication of the sensor interface smartphones. The results of both oxygen saturation level and heartbeat rate matched remarkably based on simulation and experiments by the designed oximeter over a wide range of optical spectrum on various types of the 4^{th} and 5^{th} generations of the iPod Touch and iPhone devices. However, these iPhones or iPods are expensive devices and are not used by the mass people of a middle-income country like Bangladesh [12].

Another research article intended to design an oximeter to monitor human health parameters like oxygen saturation level in real-time. The authors tried to use the best method to achieve a good accuracy of their results for both heart rate and SPO_2 considering the reliability. They tested copious MCU-based ARM cortex 32-bit and different sensors and methods and then compared it with the results taken from the literature. However, they did not explain why this method is reliable and how reliable it is [13].

A solar-powered pulse oximeter is proposed in research work to utilize solar energy for the device to increase the lifespan of the device, make it eco-friendly and cost-effective. Additionally, the device was interfaced with the Internet of Things (IoT) technology to monitor and alert the data of the blood oxygen saturation level from any remote place and also to update the monitoring device in real-time. Hence, the doctor can keep track of and monitor the patient's condition. The device was designed with the MAX30102 model by using the Eagle software [14]. However, this paper did not show any cost analysis. Due to the enhanced features, its cost must be higher.

Some other researchers evaluated the use of red and infrared-reflective PPG to extract the pulse oximetry and respiration data at eight anatomical locations of the human body at rest and during walking. They inferred that if the heart rate and SpO2 data are measured at the lowest possible location of the human body's skin, then the most accurate results may be obtained subject to the condition that there is an insignificant movement of the contact between the sensor and the skin. They aimed to find an optimum anatomical location on the human body from where a reflective PPG sensor would detect and record accurately the three most important physiological parameters, such as heart rate, SpO_2, and respiration, at rest and during walking. Their sensor took roughly 1 cm^2 of the body area [15].

To measure the two important physiological parameters like blood oxygen saturation and pulse measurement, two other researchers used a near-infrared portable tissue oximeter with a detection module based on STM32 microprocessor to obtain the oxygen saturation (SpO_2) level from the human body non-invasively. Continuous-wave spectrometers provided the semi-quantitative changes in oxygenated and deoxygenated hemoglobin in small blood vessels like arterioles, capillaries, and venules. After obtaining the values, the portable device can send the data to the smartphones of the coaches or doctors who are at remote places via GPRS/WiFi/Zigbee networks. The values can be displayed as per the need of the users. The signal produced due to the blood oxygen saturation data fluctuation is sensed by the detection module and is sent to the STM32 microprocessor to processes it by the expert decision-making system to deliver accurate data to the coaches and doctors. Their test results and measured data were found very accurate and stable [16].

Digital Signal Processing (DSP) based power electronics systems are being designed and implemented [17]. Now, this technique was found to be applied in detecting important physiological information, like ECG signals to observe it in the monitor to assist the physicians or cardiologists [18]. Besides, the DSP hardware-based system has been designed and implemented with memory, display system, and analog interfacing circuit [19]. This type of system with DSP can operate as stand-alone and to update the data in real-time according to the onboard pre-program algorithm for ECG analysis [20]. So, this processor can also be extended for designing the pulse oximeter machine. But in several research articles, it has been found that the microcontroller-based circuit can reduce the overall system costs in the case of several biomedical applications [21]-[25].

III. System Description

A. Block Diagram of the System

The system contains an Arduino microcontroller, a pulse oxygen sensor, a Liquid Crystal Display (LCD) unit, and a DC power supply unit. We would like to design the circuit in Proteus and then implement the whole system and measure the pulse oxygen saturation level. MAX30100 Arduino library function is used to convert the Analog to Digital Converter (ADC) value to get the oxygen saturation level in percentage.

The MAX30100 is an IC for pulse oximetry. It can monitor the heart-rate and pulse level. It comprises two LEDs and a photodetector, and it blends the optimized optics and low-noise analog signal processing techniques to sense the signals related to the pulse oxygen saturation level and heart-rate of the human body. The MAX30100 IC can be operated from 1.8 V and 3.3 V power supplies; however, the maximum power supplies are 2 V and 5 V respectively for these two voltage levels while it draws a current of 0.6 mA and 1.2 mA respectively at both SpO_2 and heart rate modes. Also, its power can be lowered using software with insignificant backup current, allowing the power supply to continue linked to the circuit always [26].

The DC power supply unit of 5 V supplies the required current to the microcontroller, pulse oximetry sensor, and the LCD unit that has 2 lines each having 16 characters. The complete system linking the major units of the proposed design is evident from the block diagram of Fig. 1.

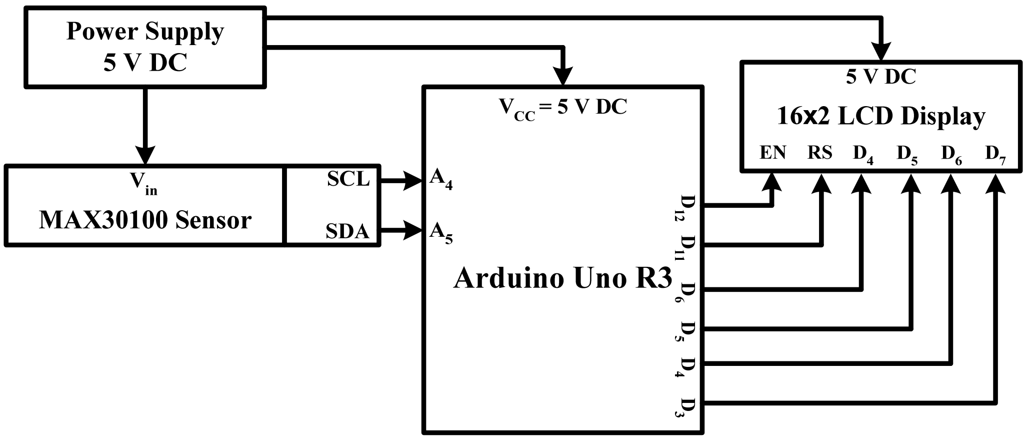

Fig. 1 Block diagram of the digital oxygen saturation level measurement system

At first, the pulse oximetry sensor unit senses the signals relevant to the oxygen saturation level of the human body from the fingertips which is positioned flanked by the two sensors, such as an optical transmitter (comprising two LEDs-one is red and another is an infra-red LED) and an optical detector (only one photodiode that can detect both the red and infra-red spectrum of light). By controlling the pulse widths of the LEDs and sample rate per second, SpO_2 data are interpreted based on the ambient temperature data.

Arduino Uno R3 microcontroller is employed here to have low power consumption, higher efficiency, in-built ADC facility, and USART mode communication capability. In-built ADC can convert the Pulse Amplitude Modulated signal into a digital format. The USART mode communication can facilitate the serial data transmission to transmit and receive the pulse oximetry data into and outside of the microcontroller respectively [25]. Arduino microcontroller is used to interpret and process the signal obtained at its input port from the sensor and then calculates the oxygen saturation level in percentage (%) using the developed assembly language program supplied to it using the personal computer. Then it sends the measured SpO_2 level to the LCD unit to demonstrate the measured value in an applicable layout as encoded in the microcontroller's program. Since the sensor IC, MAX30100 is not available in Proteus, so, an equivalent hardware circuit is designed and used in the circuit of Fig. 2 [27].

The voltage regulator IC, LM7805 is used to design a power supply unit of 5V along with 2 diodes, 2 capacitors, and a step-down center-tap transformer. It takes supply from the AC power line voltage of 220 V at 50 Hz and then rectifies it to the pulsating DC signal, which is then leveled to a pure 5 V DC by using two capacitors of 1 µF and 470 µF at the input and output terminals respectively. The capacitors eradicate harmonics and other noise interferences to the system [28].

After selecting the components of each sub-block and calculating the appropriate values of them, the complete circuit has been drawn and simulated in Proteus by applying the required signals. It is observed that the display unit can show the SpO_2 level in % as demonstrated in Fig. 2.

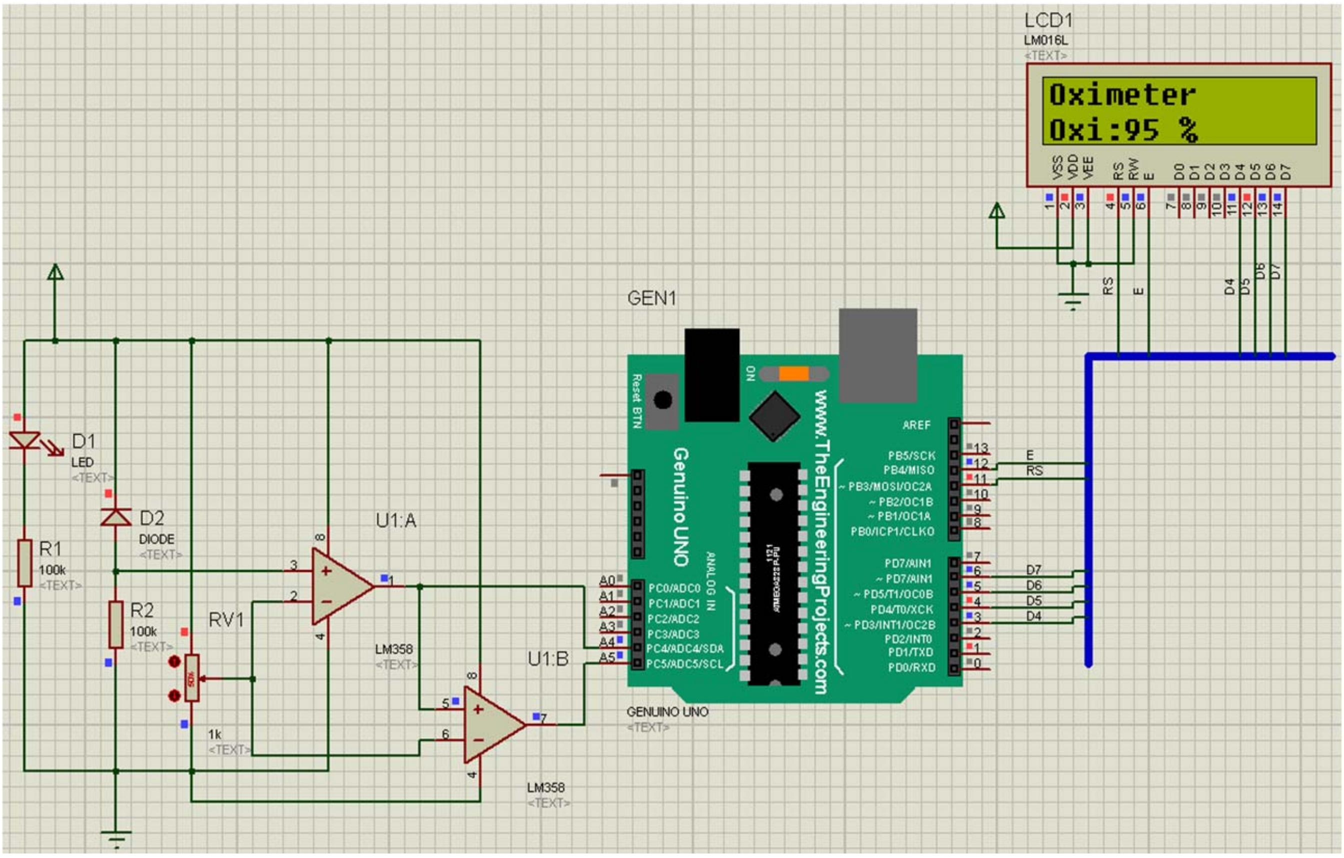

Fig. 2 Complete circuit diagram of the designed digital oxygen saturation level measurement system in Proteus

The final design of the circuit was implemented on a Printed Circuit Board (PCB), which is designed in a Proteus environment from which we got the view of the PCB as shown in Fig. 3. It shows the component placements in the Proteus environment in 3-D. The backside of the PCB is shown in Fig. 4 in which the tri-layer wiring connections are demonstrated.

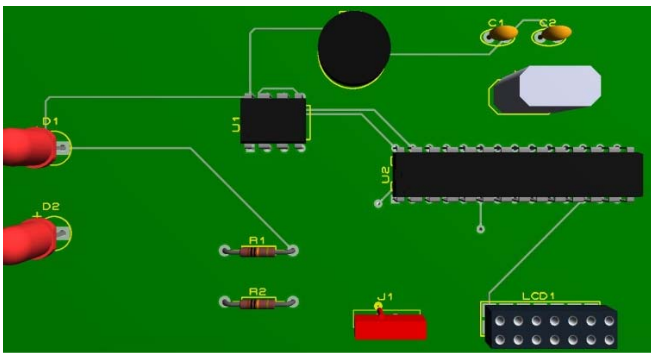

Fig. 3 View of the PCB showing the component placements from the designed circuit in Proteus

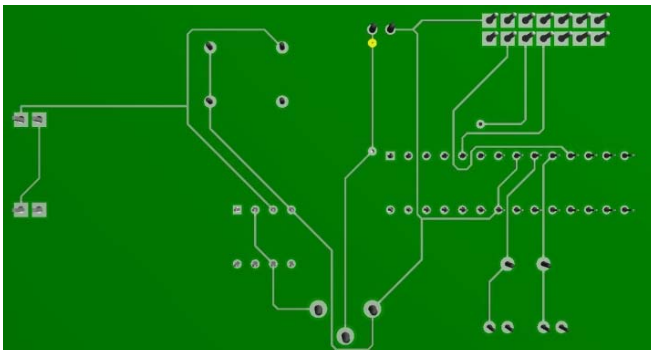

Fig. 4 Backside view of the PCB showing the tri-layer component connections of the designed circuit in Proteus

B. Software Program Design

For the Arduino Uno microcontroller to operate properly, we need to develop an assembly language program according to our logic development. There are two types of assembly language programming- the device and the application levels. The first one can drive the hardware of the system and the second one can calculate the pulse oxygen saturation level in percentage and then displays it as per the appropriate format at the selected display device.

It may be mentioned here that to program a microcontroller, an integrated software development platform is needed. The flow chart of the developed assembly language program is depicted in Fig. 5. This program reads the pulse oxygen sensor signal from its output terminal which is connected to the serial input pin of the microcontroller by scanning its serial port continuously. The clock signals of the sensor and Arduino are also connected to synchronize the data between the two units. Thus the digital data are transferred to the microcontroller's memory, from where it is processed inside the microcontroller according to the instruction sets of the assembly program, convert into the appropriate format in percentage, and finally is sent to the output port of the microcontroller to display the measured pulse oxygen saturation level data in the text format on the LCD screen of the system.

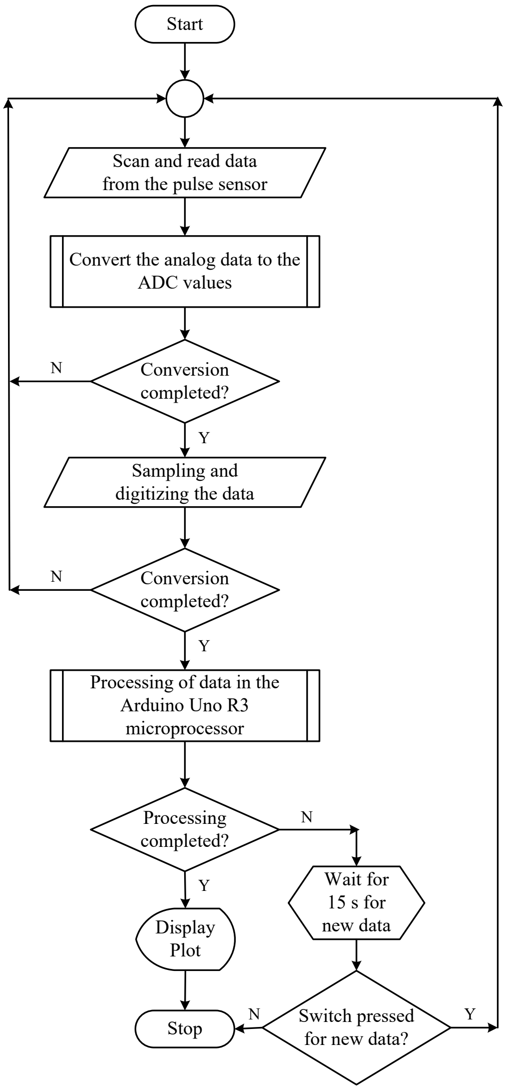

Fig. 5 Flow chart of the microcontroller program of the designed digital oxygen measuring device

To display the pulse oxygen saturation level at the designated display unit (here it is LCD screen), the software has been developed properly. The tasks of this software are to process the data to display it in the appropriate format in percentage. The output ports are properly initialized to send the data to the LCD screen's input ports connected to the output ports of the microcontroller as shown in Figs. 1 and 2. Whenever the output port gets the available data at any instant of time, the LCD screen displays the oxygen saturation value in percentage immediately.

IV. Results and Discussions

To obtain the experimental data of pulse oxygen saturation rate, the complete system developed in the Proteus was implemented using the various hardware components. The implemented system in a breadboard is shown in Fig. 6. The required power supply is 5 V (DC). This output is obtained at the LCD unit of the system.

Fig. 6 Implemented digital oxygen saturation level measurement system on a breadboard

Data are measured using both the designed digital oxygen meter and also using a pulse oxygen saturation level measurement device purchased from the market. Two such measured values for the same person at the same time are shown in Figs. 7 and 8 respectively.

Fig. 7 Measured data by the digital oxygen saturation meter

The pulse oxygen saturation level is measured for 16 people of different ages by using our designed oximeter and a standard oximeter purchased from the market at the same time. The data are presented in Table I for different aged persons. The percentages of error between the data measured by the two oximeters are calculated using (1):

$$\text{Percentage of error}, \varepsilon = \frac{DDO - DPO}{DPO} \times 100\% \quad (1)$$

where *DDO* indicates the data measured by the designed digital oximeter in percentage and *DPO* indicates the data measured by the purchased pulse oximeter in percentage.

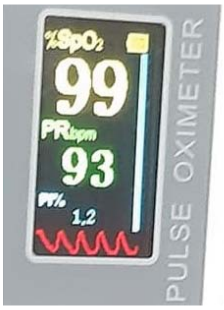

Fig. 8 Measured data by the purchased oxygen saturation meter

From Table I, we see that the people for whom data were taken aged between 12 and 57 and their age average is 27.69 years. The percentage of errors varies from 0% to 4.1% (only one person). However, the average percentage of error is very less, only 1.59%.

TABLE I
EXPERIMENTAL DATA

Sl #	Patient	Age (Years)	Measured SpO_2 Level (in %)		
			By the Designed Machine	By the Purchased Machine	Percentage of Error (in %)
1	Person1	25	97	97	0.0%
2	Person2	35	98	96	2.1%
3	Person3	25	96	98	2.0%
4	Person4	15	97	98	1.0%
5	Person5	48	97	98	1.0%
6	Person6	18	94	94	0.0%
7	Person7	12	94	98	4.1%
8	Person8	20	98	97	1.0%
9	Person9	19	94	98	4.1%
10	Person10	19	96	98	2.0%
11	Person11	18	95	97	2.1%
12	Person12	57	97	98	1.0%
13	Person13	23	96	98	2.0%
14	Person14	36	96	96	0.0%
15	Person15	45	95	97	2.1%
16	Person16	28	95	96	1.0%
Average Values		27.69	95.94%	97.13%	1.59%

Finally, the cost analysis is presented in Table II. From Table II, we see that the total implementation cost is only US$36.57. If we want to implement it on a mass scale, the implementation cost would be reduced considerably.

V. CONCLUSION

We have designed, simulated, implemented, and tested a simple and low-cost pulse oxygen saturation level measuring device using a microcontroller and a sensor. The system is portable and no medical personnel is required to measure the oxygen level of a patient. The patient can easily measure and monitor his oxygen level and sends the data for taking advice or treatment from any remote places without going to the doctors or physicians.

TABLE II
COST ANALYSIS

Sl #	Name	Quantity	Unit Price (US$)	Total Price (US$)
1	MAX30100 Finger Oximeter Heart Rate Module Model # SEN-130100	2	7.60	15.20
2	Arduino Mega R3 2560 with Cable Cost Model # 0ARD2560	1	7.60	7.60
3	16×2 LCD Display	1	1.87	1.87
4	ESP8266 NodeMcu Lua Wi-Fi Board V3.0	1	4.68	4.68
5	PCB Board	1	2.90	2.90
6	Drilling Bits	5	0.12	0.60
7	40×1 Female Headers	3	0.12	0.36
8	40×1 2.54 mm Male Header Pin	3	0.07	0.21
9	9 V, 2 A Power Adapter	1	1.40	1.40
10	Cable	-	1.75	1.75
			Total Price (US$)	36.57

In the future, we can implement it using an LED-based screen to reduce the power consumption and cost, replace the power supply with a rechargeable battery, and develop an API for the smartphone for real-time analysis of the data.

On the whole, our main goal to provide a simple, portable, and cost-effective solution for the pulse oxygen saturation level measurement for the peoples of low- and middle-income countries like Bangladesh has been attained.

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Muhibul H. Bhuyan (MIEEE'07–) became a Member (M) of WASET in 2005, born in Dhaka, Bangladesh on 25 July. He did his BSc, MSc, and PhD degrees in Electrical and Electronic Engineering (EEE) from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh in 1998, 2002, and 2011 respectively.

Currently, he is working as the Professor and Chairman of the Department of Electrical and Electronic Engineering of Southeast University, Tejgaon, Dhaka, Bangladesh. Previously, he worked at the Green University of Bangladesh, Dhaka as a Professor and Chairman of the EEE Department; Daffodil International University, Dhaka, Bangladesh as an Assistant Professor and Head of ETE Department; Presidency University, Dhaka, Bangladesh as an Assistant Professor and American International University Bangladesh (AIUB), Dhaka as a Faculty Member since June 1999. He also worked as a Researcher in the Center of Excellence Program of Hiroshima University, Japan from July 2003 to March 2004. So far, he has published over 40 research papers in national and international journals and presented over 50 research works at national and international conferences. His research interests include MOS device modeling, biomedical engineering, control system design; outcome-based engineering education, assessment, and evaluation.

Prof. Bhuyan is a Member of IEEE, USA, Executive Member of Bangladesh Electronics and Informatics Society (BEIS), and Fellow of the Institution of Engineers Bangladesh (IEB). He is a regular reviewer and technical/editorial/organizing committee member of several national and international journals and conferences. He was the Organizing Chair of the IEEE 22nd International Conference on Computer and Information Technology (ICCIT) in Dhaka, Bangladesh during 18-20 December 2019. He is the recipient of the Bangladesh Education Leadership Award (Best Professor in Electrical Engineering) in 2017 from the South Asian Partnership Awards, Mumbai, India.

Md. Refat Sarder was born in Dhaka district, Bangladesh on 12th April. He completed his BSc degree in Electrical and Electronic Engineering (EEE) from Southeast University (SEU), Tejgaon I/A, Dhaka, Bangladesh in 2020.

Currently, he is working as a Research Student in the Department of Electrical and Electronic Engineering of Southeast University, Dhaka, Bangladesh. His research interest includes biomedical engineering and system development.