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Design and Performance Analysis of an Infra-Red Based Heart Rate Monitoring System

Babatunde Ademola Iyaomolere, Olumide Akintunde Alamu

Abstract**: *The rate of the human heartbeat is an indication of the health status of the heart and circulatory system and many humans are potential candidates of stress-related health conditions due to the non-availability of a heart rate measuring device that is both affordable and easy to operate. This paper presents a study on the design and performance analysis of an efficient infrared based heart rate monitoring (HRM) system that is economical and portable. The heart rate is measured by placing the finger on an Infra-Red (IR) sensor unit composed of the IR Light Emitting Diode (LED) and a photo-diode. The heart rate is detected from the blood flow through the finger and the pulse signals pass through some filtering and amplification to be detected by the microcontroller. The HRM system employs a microcontroller, PIC16F628A which serves as a central processing unit (CPU) to process and analyze the heart beats detected as electrical signals from the IR sensor unit and converts the measured heart rate to a numerical value which is displayed via a 3-digit seven segment display. The designed HRM device is portable, durable and cost-effective. It can be used to monitor the human heart rate in both clinical and non-clinical environments with the advantage of being operated by non-professionals. The HRM system was tested in the laboratory and 50 samples of heart rates was analyzed to determine its performance level. The accuracy test results of the HRM device showed that the average error rate is 1.85%, when compared with a Blood Pressure Monitor. Hence, the performance of the HRM device is high with negligible error rate.***

Index Terms**: *Biomedical, Heart Rate Measurement, Infra-Red Sensor, Microcontroller, Pulse Detection, Signal Amplification***

I. INTRODUCTION

Heart rate serves as an indication of the health status of the human heart and helps to monitor the overall condition of the heart and blood circulatory system. A heart rate monitoring (HRM) system is a measuring device that captures the heart beats of humans and interprets the measured value in the standard units of Beats per Minutes (bpm). This makes the information about the health status of the human heart easily accessible even to a non-medical specialist [1]. Normally, when the heart is in a good health condition, then the measured heart rate should fall between the lower limit of 60 bpm and the upper limit of 100 bpm. The heart condition when the human heart rate is below the acceptable lower limit of 60 bpm is known as bradycardia condition while the heart condition when the heart rate is higher than the acceptable upper limit of 100 bpm is referred to as a tachycardia condition [2].

Conventionally, heart rate is measured by placing the fingers on a position where arteries can be easily found like the wrist and counting the distinct number of pulses over some period say 30 seconds and computing the measure heart rate in bpm. However, this method is prone to errors and found to be unreliable. In a bid to achieve better accuracy, electronic principles are usually employed to develop measuring devices to capture the human heart rates. Electrocardiogram (ECG) is one of the commonly used and accurate measuring devices but it is quite expensive and its use for the measurement of the heart rate only is not economical. Also, there are several accurate and portable HRM devices available in the form of wrist watches but the cost of these smart measuring devices are high [3].

In this paper, the circuit design of an infra-red (IR) based HRM device that provides an accurate reading of the heart rate is presented. The HRM device is portable, economical and safe for human use. The heart rate is measured by placing the finger on an IR sensor unit composed of the IR Light Emitting Diode (LED) and a photo-diode. A low power microcontroller, PIC16F628A is responsible for the central control of the HRM device and displays the pulse rate in bpm on a 3-digit seven-segment display.

The organization of this paper is as follows: literature review is presented in SECTION II while SECTION III discussed the system overview of HRM device. SECTION IV describes the circuit design and analysis while SECTION V explains the experiment procedures and results. SECTION VI concludes this paper.

II. LITERATURE REVIEW

The HRM systems are commonly used all over the world to track the health condition of the heart and blood circulatory system. Several designs have been proposed by researchers on how to improve the performance of the HRM devices. In [5], the author described the implementation of a heartbeat monitoring system by employing the Artificial Neural Network (ANN) algorithm and advanced signal processing to achieve an ECG diagnostic system that is efficient and robust. In the development of HRM devices, the power consumption needs to be efficient and so, [6] proposed a heart rate monitoring system that can both measure the heart rate and detect arrhythmia heart condition.

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* Correspondence Author

Babatunde Ademola Iyaomolere*, Department of Electrical and Electronics Engineering, Ondo State University of Science and Technology, Okitipupa, Ondo State, Nigeria, (email: ba.iyaomolere@osustech.edu.ng).

Olumide Akintunde Alamu, Department of Electrical and Electronics Engineering, University of Lagos, Akoka, Lagos State, Nigeria, (email: oaalamu@unilag.edu.ng).

A low power microcontroller, MSP430FG4816 was used for the circuit design.

The author's main focus was on creating an ECG monitoring system that can detect abnormal heart condition and alerts the user. However, it requires the expertise of a medical practitioner to operate the ECG monitoring system.

A major challenge is the high cost of acquiring these HRM devices. In [7], a microcontroller based heart rate monitor that employs the optical technology to capture the pulses from the fingers was proposed. The microcontroller processes the pulse signal by applying Fourier transformation and displaying the measured heart rate on an LCD. A buzzer alarm is also integrated in the device to indicate heart rate status. However, the device requires expertise knowledge to operate and is also not economical.

III. SYSTEM OVERVIEW

The Heart Rate Monitoring (HRM) device is composed of five major system units which includes; the Infrared (IR) sensor unit, the amplification/filter unit, the microcontroller unit, the display unit and the power supply unit. The major system units will be described in details in the following sub-sections. Fig. 1 shows the block diagram of the proposed device.

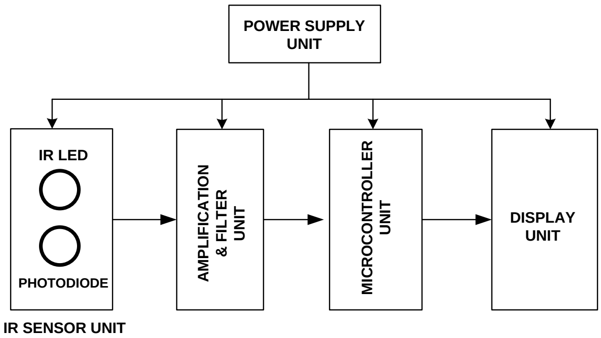

Fig. 1: Block diagram of the heart rate monitor

A. Infrared Sensor Unit

The IR sensor unit is responsible for the measurement of the heart rate by placing the fingertip over it. The IR sensor unit consists of an IR LED and a photo-diode, as shown in Fig. 2. The IR LED transmits an infrared light onto the fingertip that is placed on the IR sensor unit, and the photo-diode captures the portion of the light that is reflected back. The volume of blood inside the fingertip determines the intensity of light that is sensed by the photo-diode. Hence, the variation in the light intensity due to different heart beat pressure are detected by the photo-diode as pulses [2].

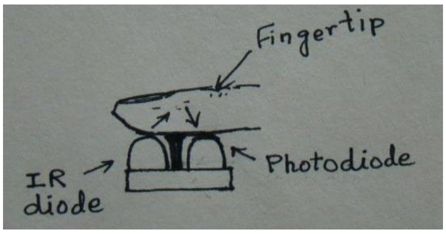

Fig. 2: Fingertip placement over the IR sensor unit [9]

B. Amplification/Filter Unit

The amplification section of the circuit used LM358 (see Fig. 3), a dual operational amplifier Integrated Circuit (IC) from Microchip which supplies a rail-to-rail output swing and operates at a single voltage source. The filtering section of the circuit consists of two active low pass filter of same specification. The heart rate signals detected by the IR sensor unit are small electrical signals that are susceptible to the ambient noise in the environment. Hence, the filtering process helps to eliminate any unwanted frequency in the heart rate signal. Also, the two stage amplification helps to strengthen the weak signal coming from the IR sensor unit.

The gain, A of each filter is given by [2]:

$$A = 1 + \frac{R_f}{R_i} \quad (1)$$

Where;

R_i is the input resistor value

R_f is the feedback resistor value

While the cut-off frequency, f_c of each filter stage is [2]:

$$f_c = \frac{1}{2\pi R_f C_f} \quad (2)$$

Where;

C_f is the feedback capacitor value.

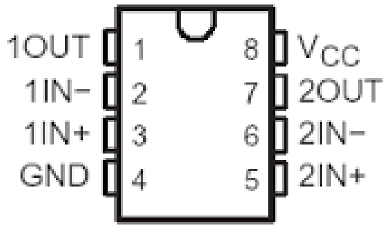

Fig. 3: Pin configuration of LM358 [2]

C. Microcontroller Unit

The microcontroller unit performs the function of the central processing and coordination of other system units. The PIC16F628A microcontroller is an 8-bit CMOS Microcontroller with an 18-pin configuration and has a flash memory. This microcontroller is considered because of the design requirements for portability, low-cost and fast response time. An external crystal of 4 MHz is required for the proper operation of the microcontroller [2]. Fig. 4 shows the pin configuration of the PIC16F628A microcontroller unit (MCU).

D. Display Unit

The display unit is a 3-digit seven segment module with a common anode (CA) PIN configuration and employs multiplexing technique to display the measured heart rate (see Fig. 5). The segments a-g of the display unit are driven via the microcontroller's PORTB pins RB0-RB6, respectively.

The unit's, ten's and hundred's digits are multiplexed with RA2, RA1, and RA0 port pins [9].

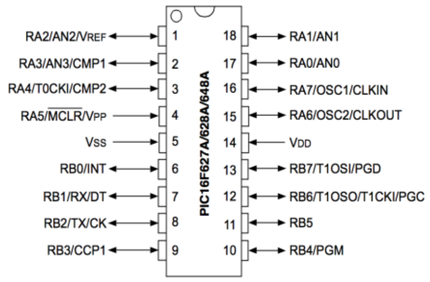

Fig. 4: Pin configuration of PIC16F628A [8]

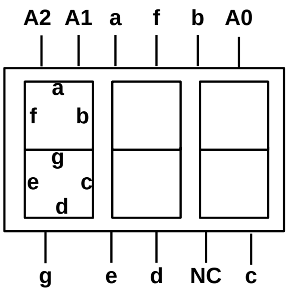

Fig. 5: Pin configuration of 3-digit CA 7-segment Display

E. Display Unit

This system is designed to run on a 9V battery power source. It is expected to deliver the necessary voltage level needed by the microcontroller and the other devices. These devices required a 5V supply instead of the 9V, hence the need for a voltage regulator. The 78L05 three terminal voltage regulator is used to regulate the 9V to 5V supply for the whole design. Fig. 6 shows the pin configuration of the 78L05 voltage regulator.

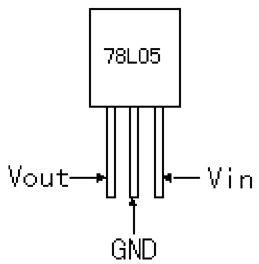

Fig. 6: Pin configuration of 78L05 voltage regulator [10]

IV. CIRCUIT DESIGN AND ANALYSIS

The circuit design of the HRM device compresses the five major system units into two physical system units namely: the HRM Sensor Unit (see Fig. 7), which houses the Amplification/Filter unit and the IR Sensor unit; and the HRM Control Unit (see Fig. 8 and 9) which is composed of the Microcontroller unit, the Display unit and the Power Supply unit. In this section, the circuit design and analysis of the HRM system units will be described in details.

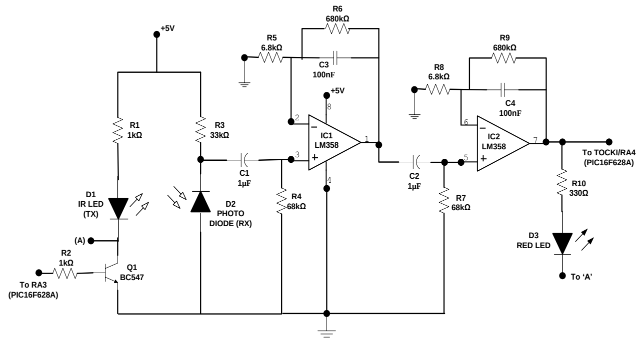

Fig. 7: Circuit diagram of the HRM Sensor Unit [9]

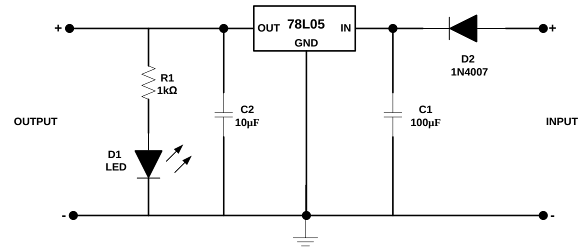

Fig. 8: Circuit diagram of the Power Supply Unit [12]

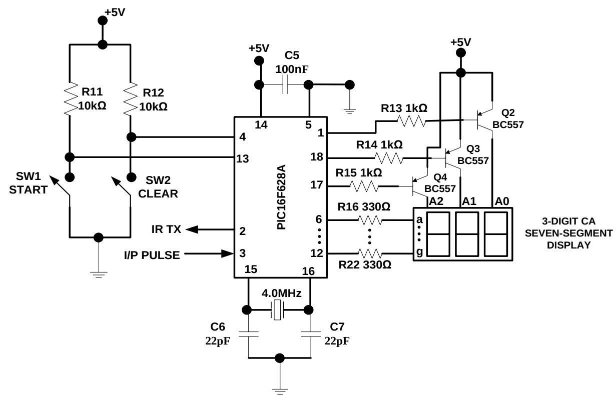

Fig. 9: Circuit diagram of the HRM Controller Unit [9]

A. Circuit Analysis of the IR Sensor Unit

In the design of the IR sensor unit, the intensity of the IR light transmitted to the photo-diode should be minimal so that the photo-diode can easily detect the varying heartbeat signal. Hence, the main purpose of the resistor R1 in series with the IR LED is to reduce the intensity of the infrared light transmitted by limiting the current supplied to the IR LED. There is no fixed value for the current limiting resistor as it depends on the specifications of both the IR LED and the photodiode used for the circuit implementation [9]. Fig. 10 shows the practical test circuit that was used to find the appropriate value of the series resistor for the IR diode employed. The variable resistor was tuned until a pulse was detected by the amplification/filter unit, the RED LED blinks whenever a pulse is detected. The minimum resistance value that was measured was 890Ωbut 1kΩ was chosen for the circuit design.

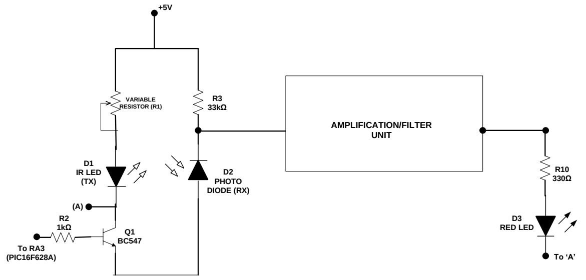

Fig. 10: Test circuit to determine the limiting resistance [9]

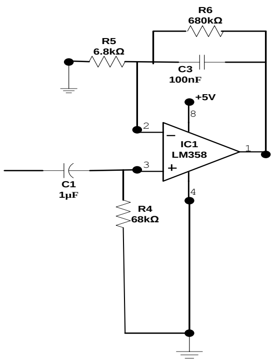

Fig. 11: First Filter/Amplification stage [2]

B. Circuit Analysis of the Amplification/Filter Unit

The amplification operation is performed by LM358 which has two operational amplifiers. The circuit diagram for the first stage of the amplification is shown in Figure 11 and this will be used for the purpose of the circuit analysis.

To determine the gain, A_1 for the first filter stage, we apply the formula in equation (1) given as:

$$A = 1 + \frac{R_f}{R_i}$$

where $R_f = 680k\Omega$, $R_i = 6.8k\Omega$;

This implies that;

$$A_1 = 1 + \frac{680\times10^3}{6.8\times10^3} = 101$$

Since, the second filter stage has the same circuit components and values as the first stage; this implies that the Gain, A_2 will be 101. Considering the circuit diagram shown in Fig. 7, the two filter stages are cascaded. Hence, the total Gain, A_T is given as;

$$A_T = A_1 \times A_2 \qquad (3)$$

Therefore, $A_T = 101\times101 = 10201$

Also we need to determine the cut-off frequency, f_c of each filter stage, we recall equation (2);

$$f_c = \frac{1}{2\pi R_f C_f}$$

where $R_f = 680k\Omega$, $C_f = 100nF$;

This implies that;

$$f_c = \frac{1}{2\pi\times680\times10^3\times100\times10^{-9}} = 2.34Hz$$

C. Microcontroller Programming

The complete program was written and compiled in the MikroC Pro software and an assembled HEX file is created from the compiling process. The program is designed such that the calculation for the heartbeat in beat per minute (bpm) is given as;

$$pulse\,rate = pulse\,count \times 4; \qquad (4)$$

where the pulsecount is a variable that stores the number of pulse detected within a period of 15 seconds while the pulserate is a variable that holds the value of the final heart rate per minute derived by equation (4).

The hardware used for the programming is the JDM Programmer (see Fig. 12 and 13 for the circuit diagram and circuit design), which is a High-Voltage Programmer which is connected to the serial port (COM port) of the Personal Computer (PC). It takes the programming voltage directly from the PC's COM port, so no separate power supply is needed. The HEX program file was written into the FLASH memory of the PIC by the PICPgm software, which supports a wide range of PICs.

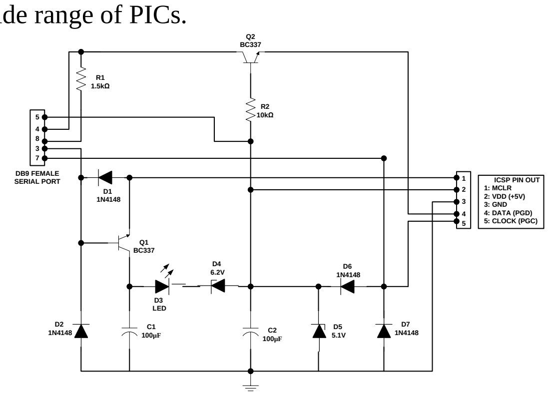

Fig. 12: Circuit diagram of JDM serial PIC programmer [11]

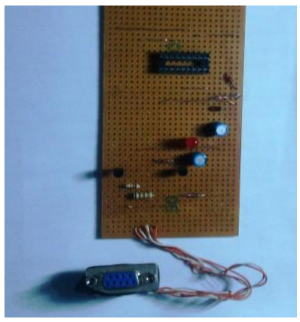

Fig. 13: Circuit implementation of the JMD programmer

D. Working Principles

The HRM device is powered ON by a Power Switch which connects the 9V battery to the power supply unit. The 9V supply is regulated to an output of 5V by 7805 IC and the GREEN LED is an indication of POWER ON/OFF. When the power is turned ON, zeros will be on the display unit for few seconds and the display goes off after some seconds. The index finger is placed on the IR LED and Photodiode pair and the START button is pressed, once the HRM Sensor unit detects a pulse at the finger tips, the RED LED blinks.

In order to conserve power, the microcontroller was programmed to supply power to the IR sensor unit for a period of 15 seconds, anytime the START button is pressed. The RESET button is available to restart the microcontroller in case of a possible interference and disturbance on the part of the IR sensor unit. The microcontroller estimates the average heart rate (pulse rate) in bpm and displays the result on the output display unit after the 15 seconds period of measurement. Fig. 14, shows the step by step operations and processes being performed in the HRM system.

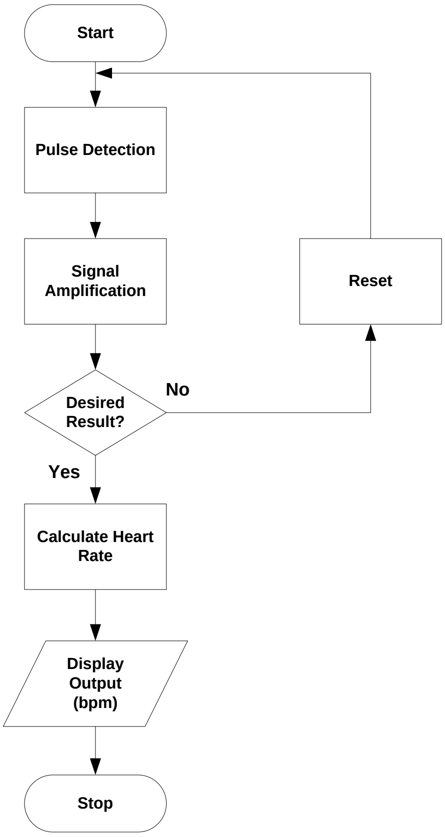

Fig. 14: The flowchart of the Algorithm [2]

V. EXPERIMENT PROCEDURES AND RESULTS

A. Test Procedures

The heart beat signals generated from the HRM sensor unit was captured on the oscilloscope. The test probe of the oscilloscope is an alligator clip; the positive probe is connected to designated points of measurements while the negative probe is connected to the ground/earth of the device. The VOLT/DIV control of the oscilloscope was set to 50mV while the TIME/DIV control was set to 5ms, the Input Channel is CH1 and the input signal mode was set to Alternating Current (AC).

The accuracy of the HRM measurements was determined by comparing the HRM device's measurement with the Blood Pressure (BP) monitor's measurement. The BP Monitor (see Fig. 20) is a digital LCD display device that has the capability of measuring both blood pressure and heart rate. The test probe is a cuff which inflates when the START button is pressed. For the purpose of this accuracy test, the cuff is put around the wrist of the tested persons.

B. Laboratory Test Results

In the previous section, it was mentioned that the objective of the laboratory test is to check the functionality of the Amplification/Filter unit. The oscilloscope was employed to capture the waveforms of heart beat signals at three measurement points namely; the output of the IR Sensor Unit, the output of the First Filter Stage and the output of the Second Filter Stage.

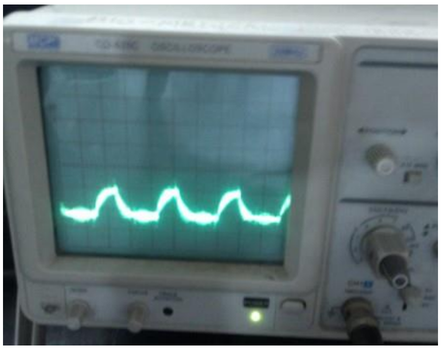

Fig. 15: The waveform of the IR Sensor Unit Output

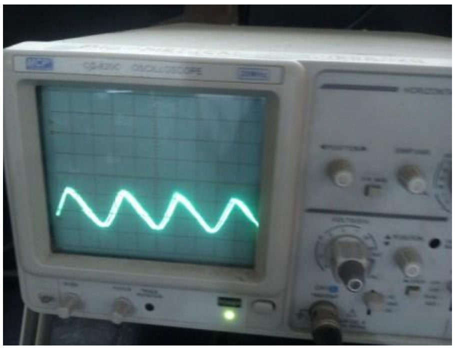

Fig. 16: The waveform of the First Filter Stage Output

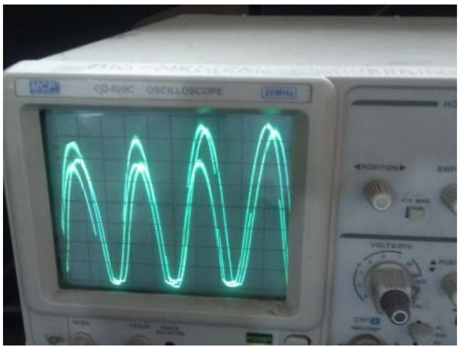

Fig. 17: The waveform of the Second Filter Stage Output

C. Accuracy Test Results

In order to perform this accuracy test, five (5) persons were selected for the testing and they were tested five (5) times using the HRM device and the BP Monitor in sequential order. Figure 19 and 20; show an instance of the measurement results from both devices while Table 1 displays the experimental results of the heart rate measurements from the HRM device and the BP monitor.

Table 1: The results of the heart rate measurements from the HRM and BPM

	Person A		Person B		Person C		Person D		Person E	
Test Count	**HRM (bpm)**	**BPM (bpm)**	**HRM (bpm)**	**BPM (bpm)**	**HRM (bpm)**	**BPM (bpm)**	**HRM (bpm)**	**BPM (bpm)**	**HRM (bpm)**	**BPM (bpm)**
1	80	80	68	72	68	70	72	71	80	75
2	80	77	68	67	72	72	72	70	80	81
3	80	76	68	67	64	67	72	72	76	79
4	84	83	68	67	64	68	72	70	80	78
5	84	80	68	67	64	67	68	67	84	83
Average Beat	**81.6**	**79.2**	**68**	**68**	**66.4**	**68.8**	**71.2**	**70**	**80**	**79.2**
Error Rate (%)	**2.94**		**0.00**		**3.61**		**1.69**		**1.00**	

The error rate formula is given as;

$$Error\ \text{rate}\,(\%) = \frac{|H - B|}{H} \times 100 \qquad (5)$$

where B is the BP Monitor heart rate value
and H is the HRM device heart rate value

In this paper, the error rate is estimated from the average heart rate measured from each tested persons.

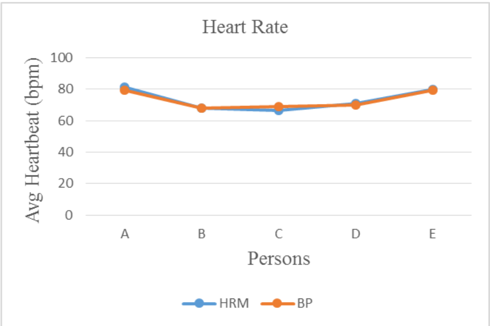

Fig. 18: The graph showing the measured average heartbeat

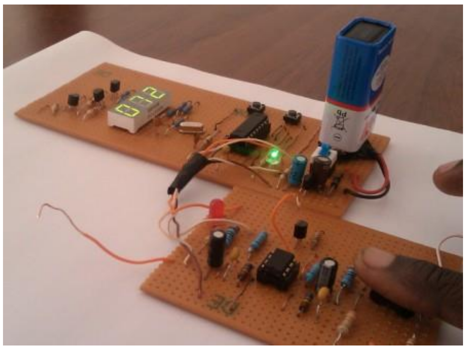

Fig. 19: HRM device displaying a heart rate measurement

Fig. 20: BP Monitor displaying a heart rate measurement

D. Discussions

In Fig. 15, it was observed that the original heart beat signal is very small in amplitude and contains much noise such that the microcontroller cannot pick the signals as distinct pulses. Fig. 16 shows that the original heart beat signals have been filtered and amplified but the signal power is still very low to be detected and hence, there is a need for another filtering and amplification. In Fig. 17, the waveform shows that the amplitude is high enough to be detected by the microcontroller and the filtering made the signal more sinusoidal. The results of the heart rate measurements from the HRM device and BP Monitor summarized in Table 1 show that the error is very minimal with the average error rate of 1.85%. From the curve plotted in Fig. 18, the RMSE value is 1.6492 and this further proves that the HRM system has high efficiency with minimal error rate.

VI. CONCLUSION

In this paper, the design and construction of an infrared based heart rate monitoring system was described. The results from the oscilloscope waveforms show that the human heart rate can be detected from changes of blood flow through an index finger.

The accuracy test shows that heart rate measurements from the HRM device are in close agreement with that of the BP monitor. Hence, the performance of the HRM device is high with negligible error rate and can be recommended for heart rate monitoring in both clinical and non-clinical environments.

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AUTHORS PROFILE

Babatunde Ademola Iyaomolere received B.Sc. Degree in Electrical and Electronics Engineering with First Class Honours from Olabisi Onabanjo University, Nigeria in 2009. He completed his M.Sc. program in Electrical and Electronics Engineering (Communication option) from University of Lagos, Nigeria in 2016. Presently, he is a doctorate student at the Department of Electrical and Electronics Engineering, Federal University of Technology, Akure, Nigeria. He is a registered Engineer with the Council for the regulation of Engineering in Nigeria (COREN) and also a Corporate Member of Nigerian Society of Engineers (NSE). His research interests are in Microcontrollers, Signal Processing, Radio Wave Propagation, and mmWave networks. He is currently a lecturer at the Department of Electrical and Electronics Engineering, Ondo State University of Science and Technology, Nigeria.

Olumide Akintunde Alamu graduated from Ladoke Akintola University of Technology, Ogbomoso, Nigeria in 2009 where he received B.Tech (Hons) Degree in Electronic and Electrical Engineering. He received M.Sc. Degree in Electrical and Electronics Engineering (Communications option) from University of Lagos, Nigeria in 2016 and currently on Ph.D. programme in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. His research interest is in Self-Organization in Wireless Cellular Heterogeneous Networks. He currently lectures in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He is a registered Engineer with the Council for the regulation of Engineering in Nigeria (COREN) and also a Corporate Member of Nigerian Society of Engineers (NSE).