

Measurement of Heart Rate Using Photoplethysmography

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Abstract—Heart rate, or pulse, is one of the vital signs used to measure basic functions of human body. Heart rate is the number of times one's heart beats per minute. The method that has been used to measure heart rate in this project is widely known as photoplethysmography (PPG). The constructed device can be used to find out the heart rate of a person and to analyze readings using existing software. Theoretically, any body part can be used to measure heart rate through the sensor of the device, although fingertips and earlobes are commonly targeted.

Index Terms—Heart Rate Measurement, Pulse Measurement, Photoplethysmography, Vital Signs.

I. INTRODUCTION

Vital signs are the indicators of a person's essential body functions. There are four vital signs: heart rate, blood pressure, respiratory rate and, body temperature. Commonly it is seen in the households that people have devices to measure blood pressure. In this project a device has been developed to measure another vital sign, heart rate.

Apart from indicating the soundness of the heart, heart rate helps assessing the cardiovascular system [1]. Analysis of heart rate helps in diagnosis and detection of coronary diseases. Measuring heart rate has a long tradition in medicine as a non-invasive indicator of illness [2]. An elevated resting heart rate has been associated with cardiovascular [3], [4], [5] and all-cause mortality [6], [7] independent of major cardiovascular risk factors, and with cancer mortality [8].

The normal range of heart rate among adults is 60-100 beats per minute (bpm) [9]. Heart rate varies with body fitness. The fitter a person is, the lower is his heart rate. If heart rate is higher than normal the condition is known as tachycardia, in the opposite case it is known as bradycardia [10].

There are many devices available in the market to measure heart rate. The constructed device brings about some major changes compared to the available ones. Firstly, this is a cost-effective option to measure heart rate. Whereas the price of the devices already available in market ranges from 25 USD to 60 USD [11], the device that has been constructed in this project cost roughly from 10 USD to 12 USD. Secondly, the device provides an easy way to interface with personal computers and mobile phones. This opens up opportunities to perform further analysis on the recorded data. Thirdly, although there are a few analog devices to measure heart rate, the patient needs help from another person to do so. This device can be used without any need of assistance from others. Finally, the

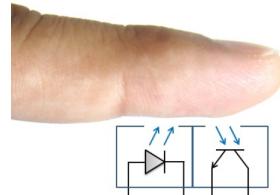


Fig. 1. Reflective photoplethysmography.

device is easy to use. The user only needs to place a fingertip on a sensor, as opposed to enclosing fingertip inside a cap or wearing a cuff.

The main component that has been used to detect heart rate in this project is an optical reflective sensor. A PIC microcontroller has been used to count heart beats. Optionally an Arduino board can be used to interface the device to personal computer for analysis.

II. BACKGROUND

The word plethysmograph has been derived from two Greek words - 'plethysmos', meaning increase; and 'graph', meaning write [12]. It is an instrument mainly used to determine and register the variations in blood volume or blood flow in the body which occur with every beat of the heart [13]. Plethysmography is the volumetric measurement of an organ, resulting from fluctuations in the amount of blood or air it contains. The change in blood volume is synchronous to the heart beat, so it can be used to detect heart rate. Photoplethysmography is just a means of plethysmography that uses optical techniques. There are two basic types of photoplethysmography: transmittance and reflectance [14], [15]. Reflectance photoplethysmography has been used in this project. In reflectance photoplethysmography, a light source and a light detector are placed on the same side of a body part [16] - for example, underneath the fingertip as shown in figure 1. The light source generally used is an infrared light emitting diode, and the detector generally used is a phototransistor. When the fingertip is illuminated by the source, three things will happen depending on the volume of blood in the fingertip: certain amount of the light will be absorbed, certain amount of the light will be transmitted, and certain amount of light will be reflected [17]. The intensity of the reflected light

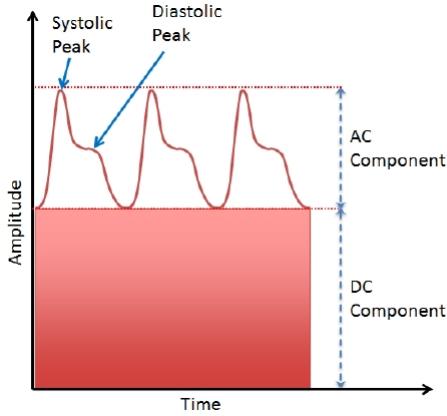


Fig. 2. PPG signal.

varies with the volume of blood in the fingertip, which in turn varies in accordance with heart beat. Specifically, lower intensity of reflected light indicates higher volume of blood and vice versa [18]. A plot of this varying intensity of light with time is known as photoplethysmographic signal [19]. The time period of each pulse in the signal is dictated by heart beat and the amplitude by the concentration of various constituent parts of arterial blood [20]. The PPG signal is composed of two components: AC and DC [21]. The AC component is superimposed on the DC component. The AC component is the result of pulsatile changes in arterial blood volume [22]. As this arterial blood volume is synchronous with the heart beat, the AC component can be used to measure heart rate. The DC component relates to the tissues, bones, and average blood volume [23]. This DC component must be removed to analyze the AC component. As it happens, the AC component is a very small portion of the whole signal. As a result the resulting PPG signal must be filtered and amplified before it can be utilized in detection of heart rate. Figure 3 shows a PPG signal as seen in a DSO NANO V3 oscilloscope.

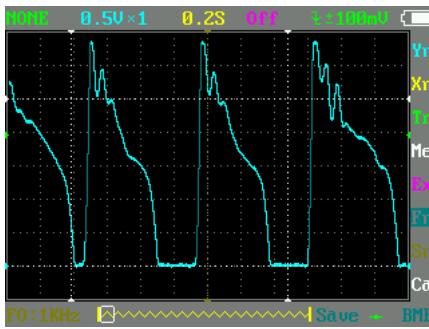


Fig. 3. PPG signal in oscilloscope.

III. CIRCUIT CONSTRUCTION

The full circuit has been constructed in three steps: external biasing circuit, first stage signal conditioning circuit, and second stage signal conditioning circuit [24]. The circuit has

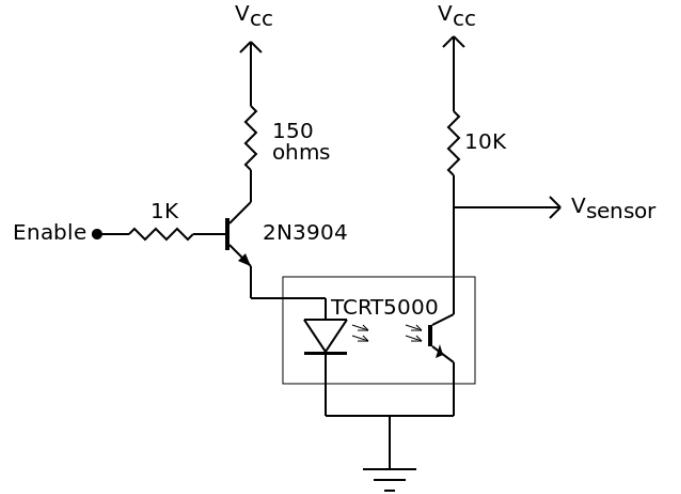


Fig. 4. External biasing circuit.

provision for integration with microcontrollers and single-board computers. In this project the circuit has been integrated with a PIC microcontroller and an Arduino board.

A. External Biasing Circuit

This part of the circuit provides reading from the sensor. The optical reflective sensor that has been used is TCRT5000 from Vishay. Basically it is a single unit having both the infrared light emitter and the phototransistor placed side by side. The output of the sensor is synchronous to the heart beat. As the sensor is contained in a leaded package, it is less susceptible to ambient light. Another sensor suitable for use here is TCRT1000, also from Vishay. TCRT1000 is less susceptible to ambient light than TCRT5000. While measuring heart rate it is important that the person minimizes movement as much as possible. Generally movements might cause extra changes in blood volume, so the sensors are susceptible to movement. The enable pin can be controlled through a microcontroller. If the only concern is detection of heart beat, the enable pin can be fixed at high logic level. Heart beat can then be understood by observing blinking of an indicator LED at a later part of the circuit.

Although 2N3904 has been used as the required npn transistor, any general purpose npn transistors such as BC547 or 2N2222 can be used.

B. First Stage Signal Conditioning

This stage of the circuit removes the DC component of PPG signal. It also amplifies the AC component by a factor of 101. A passive high pass filter is used to filter out the DC component. An active low pass filter is used to boost the AC component. The general purpose op amp LM324 has been used to construct the active low pass filter. Other possible options for op amps include, but are not limited to, LM358, MCP6004 and MCP602. In essence a band pass filter has been used to extract required signal. The passive high pass filter

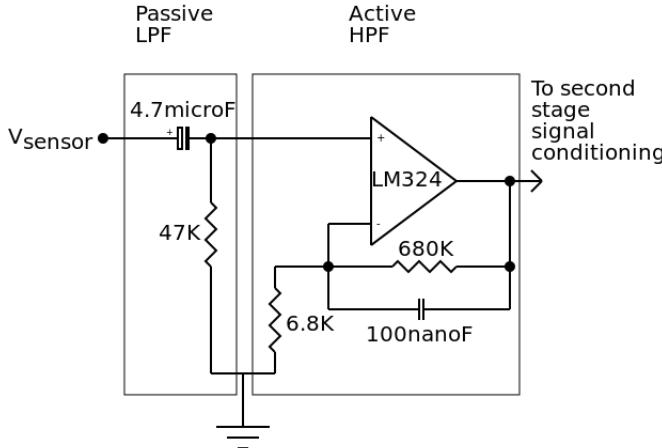


Fig. 5. First stage signal conditioning.

has a cutoff frequency of 0.7Hz . Different combinations of resistors and capacitors can be used to achieve this value. The particular values used for this circuit are $47\text{K}\Omega$ and $4.7\mu\text{F}$. The cutoff frequency for chosen values can be found using equation 1, where R is the value of resistor and C the value of capacitor.

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 47\text{K}\Omega \times 4.7\mu\text{F}} \approx 0.7\text{Hz} \quad (1)$$

The active low pass filter has a cutoff frequency of 2.34Hz . The particular values used for resistor and capacitor are $680\text{K}\Omega$ and 100nF respectively. The cutoff frequency for chosen values can be found using equation 2.

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi \times 680\text{K}\Omega \times 100\text{nF}} \approx 2.34\text{Hz} \quad (2)$$

The gain of this op amp for the chosen values of resistors and capacitors can be found using equation 3, where R_2 is the negative feedback resistor.

$$G = 1 + \frac{R_2}{R_1} = 1 + \frac{680\text{K}\Omega}{6.8\text{k}\Omega} = 101 \quad (3)$$

C. Second Stage of Signal Conditioning

The output of the first stage of signal conditioning is fed into the second stage of signal conditioning. The second stage of signal conditioning is actually a clone of the first stage. So the values calculated at section III-B are also valid for this stage. This too gives a gain of 101, resulting in final gain of 10201. If such a large gain is not desirable, a potentiometer can be attached between ground and output of first stage signal conditioning. The output of this stage can further be supplied to a non-inverting buffer stage to lower the output impedance. This might be needed if an ADC channel of a microcontroller is used to read the amplified PPG signal. The output of second stage of signal conditioning can be used to drive a LED, which acts as indicator an indicator of pulse.

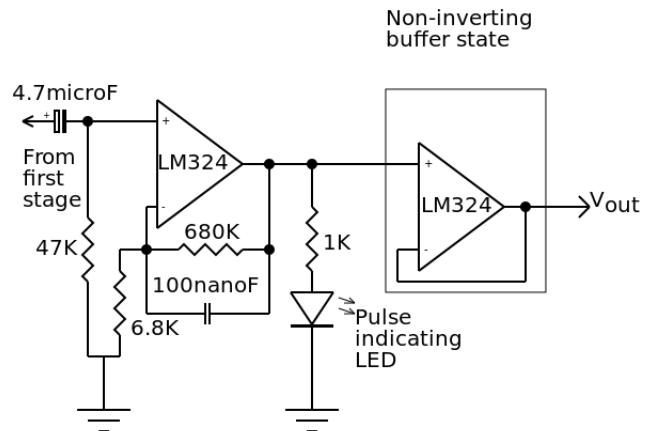


Fig. 6. Second stage signal conditioning.

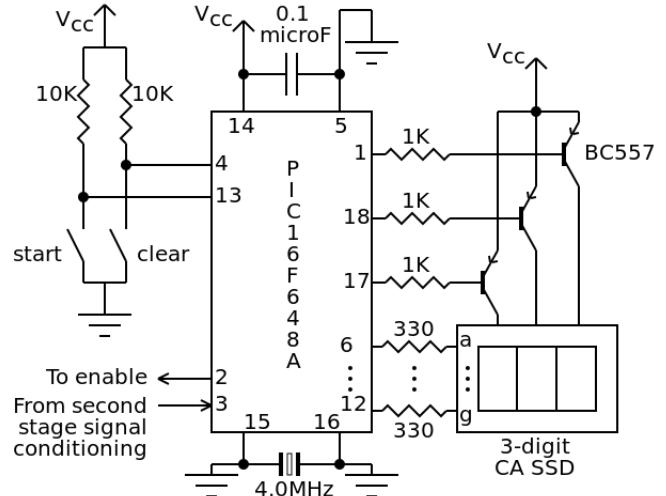


Fig. 7. Interfacing with PIC16F648A.

IV. INTERFACING TO MICROCONTROLLERS

Microcontrollers can be used to detect the output of the signal conditioning stage, and count heart beats accordingly. The only module required to count heart beats is the timer module. So any microcontroller having the timer module can be used in this device. This opens up a wide range of choices for microcontrollers, even allowing the use of those that are very simple. A PIC16F648A microcontroller has been used in this project. The connections of the microcontroller can be seen in figure 7 along with pin numbers.

The output of the signal conditioning stage is counted for 15 seconds and multiplied by 4 to get the heart rate. The result can then be shown with the help of seven segment displays. In this project three separate displays have been used. Alternatively three displays packaged as a single unit can also be used. An experiment has been conducted on three persons, taking three

TABLE I
EXPERIMENTAL RESULTS.

person	reading	measured heart rate (bpm)	actual heart rate (bpm)	percentage error (%)
1	1	72	75	4.00
	2	68	73	6.85
	3	68	72	5.55
2	1	76	79	3.80
	2	80	82	2.44
	3	80	80	0.00
3	1	64	67	4.48
	2	68	69	1.45
	3	68	71	4.23

seperate readings for each. The result has been presented in table I.

Output from the non-inverting buffer stage can be fed into microcontroller for further analysis. In this project the output of the non-inverting buffer has been fed into an Arduino UNO board. Graphs were obtained from the supplied signal using an existing software [25]. In figure 8 the software can be seen in action.

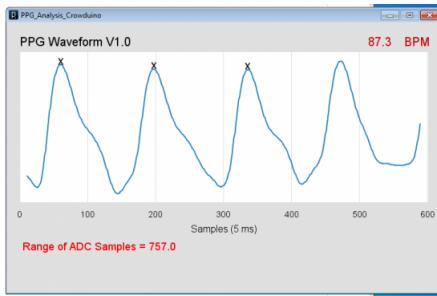


Fig. 8. PPG waveform and heart rate displayed on computer screen.

Currently the software just shows graph based on the input signal. As a future endeavor an improved software can be created with extra features such as data logging.

To ensure consistency in supplied voltage a decoupling capacitor of $0.1\mu F$ has been used. In DC circuits capacitors act as open circuit. When the circuit is powered up the capacitor starts to acquire charges. If due to noise the supply ever decreases from the previous value, the capacitor discharges to make up for the deviation.

The internal oscillator of microcontrollers generally tend to be susceptible to heat. When the microcontroller is used for a considerable amount of time it generates heat which can affect the functionality of internal oscillator. To avoid this from happening an external oscillator of $4.0MHz$ has been added.

Three pnp transistors have been used to control the common anode seven segment displays. The BC557 has been chosen as the pnp transistor. Possible alternatives include, but are not limited to, 2N5087 and BC327.

For displaying the result common anode seven segment displays have been used. If desired the output can also be displayed in an LCD module. Three separate seven segment

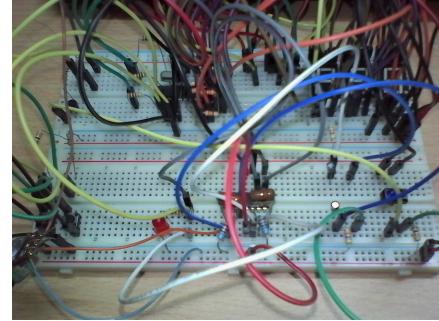


Fig. 9. Device constructed on breadboards.

displays have been used to show the result. To minimize the amount of wiring, it is better if three digit packages are used. The three displays are never really driven together. They are lit one by one at a fast pace so as to deceive the viewer's eyes that they are all lit at once.

The Timer0 module of PIC16F648A has been used to count heart beats. The heart beats are counted for fifteen seconds and multiplied by four to get beats per minute (bpm). If it is desired that the microcontroller counts for full one minute, the microcontroller has to be programmed differently.

The circuit has two buttons for controlling its actions. At first the clear button needs to be pressed once. The seven segment displays will light up for a moment. Once they fade away the user can start measuring heart rate. To start counting heart beats the user needs to place finger over the optical reflective sensor and press the push button marked start. The clear button is used to reset the microcontroller's internal registers. If the user wants to discard the current reading midway it can be done by pressing this clear button.

V. REMOTE HEART RATE MEASUREMENT

As a future improvement, the device can be used to measure heart rate remotely. Conceptually the system will work on two ends. At one end the person whose heart rate needs to be measured will be aided with the created device. Both ends will have a single board computer such as the MSP430 or equivalent, along with necessary wireless shield. At the other end the MSP430 can be further connected to a computer via RS232. A schematic diagram of the system can be seen in figure 10.

Any SBC (single-board computer) can be used in place of MSP430 provided it meets a couple of conditions. Firstly, the SBC must have wireless support. Most SBCs do not come with wireless shields by default, but have the provision of adding as a separate module. Secondly, the SBC should have RS232 port or alternatives for serial communication. Once the data is at the other end it can be processed as required. A software can be developed to aid the process of data visualization. Data logging can be a nice addition to keep record of heart rates.

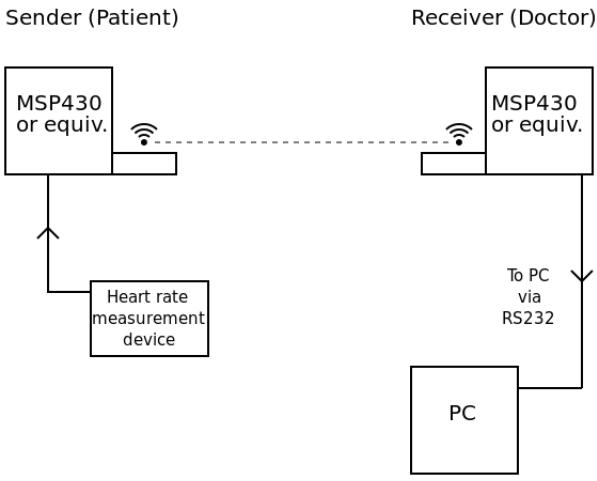


Fig. 10. Remote heart rate measurement.

VI. CONCLUSION

The device produces results which are in the acceptable range. Compared to other available options, this is a cost-effective solution to monitor heart rate. However, with a few changes the device can be made a bit more reliable. Currently while measuring the heart rate the body part held against the sensor must be kept very still. Even a slight movement results in a bit of variation. This can be avoided by using a different optical reflective sensor. A sensor based on transmittance PPG could also be used for comparison, as they are less susceptible to movement. Studies have shown that PPG can also be used to measure peripheral capillary oxygen saturation (SpO_2) [26], blood pressure [27], and respiratory rate [28]. If future studies ensure acceptable results for blood pressure, oxygen saturation and respiratory rate using PPG; attempts can be taken to devise a single module having all four features. As the basic mechanism is same, chances are the circuitry will be similar, resulting in a compact device. This will in turn result in a cost-effective way to create a device capable of measuring heart rate, blood pressure, oxygen saturation and respiratory rate.

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