Coupled PPG-ECG Blood Pressure Monitoring Device for Hypertension Detection

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Abstract*—Hypertension, or high blood pressure, is a medical condition that can lead to numerous life-threatening diseases. The current method for measuring blood pressure using a sphygmomanometer has numerous drawbacks, including inaccurate measurements, arm soreness, inability to continuously monitor, among others. This proposal will look at a unique, non-invasive wearable device to measure blood pressure, coupling the existing methods of photoplethysmography (PPG) and electrocardiogram (ECG) sensors. The peak of the PPG waveform—the systolic peak—and the peak of the ECG waveform—the R-wave—will be analyzed to determine the pulse transit time (PTT). The difference between the time of the PPG systolic peak and the ECG R-wave peak is the PTT, which can be used to determine the blood pressure of an individual. The overall design comprises of 3 parts. The output of the PPG sensor will feed into the first circuit, while the output of the ECG electrodes will feed into the second circuit. Both circuits will trigger individual timers that will allow for the calculations of PTT and blood pressure, which will be displayed on the wearable watch-like device. With this proposed bioinstrumentation, early diagnosis of hypertension can be made in patients who are at risk of hypertension. Moreover, the employment of this device would bring about medical attention and allow for appropriate medical care to prevent severe hypertension.

Keywords*—hypertension, blood pressure measurement, photoplethysmography (PPG), electrocardiogram (ECG), pulse transit time (PTT)

1. Introduction

About 50% of individuals residing in the United States of America suffer from hypertension, a medical condition characterized by high blood pressure (BP) [1], and 46% of adults are not aware of the fact that they have it [2]. Hypertension can be caused by numerous factors – unhealthy eating habits, lack of exercise, stress – but it can also be genetic [1]. Over 12.8% of annual deaths are due to hypertension worldwide [2]. With so many factors playing into hypertension, and the life-threatening nature of the condition, the need for continuous monitoring in both medical and at-home settings is evident. However, the device proposed is being developed primarily for in-patient care, so that doctors can monitor a patient's blood pressure continuously in a non-disturbing manner.

An ECG sensor uses up to 12 electrodes to record the electrical activity of the heart. For this case, 3 leads will be placed on the patient: upper right arm (RA), upper left arm (LA), and driven right leg (DRL). These leads will be connected to the watch, which will allow for the analysis of blood pressure. The PQRST waves constitute the ECG waveform, which represents the various phases of the heartbeat [3] (Fig. 1). The R-wave, which represents the ventricular depolarization, is indicative of the pumping of blood from the heart to the body [4]. This is the initial time measurement needed to calculate the PTT.

A PPG sensor is an inexpensive and non-invasive way to measure blood pressure. The sensor utilizes light and a photodetector on the skin to measure blood circulation [5] (Fig. 2). The peripheral pulse wave that the PPG detects illustrates a systolic peak and a diastolic notch. The systolic peak corresponds to the maximum peripheral blood volume during concentration, which will effectively give the amount of time needed for the pulse to reach the area where the PPG sensor is—the wrist for this specific device [6]. This is the second time measurement needed for the calculation of PTT.

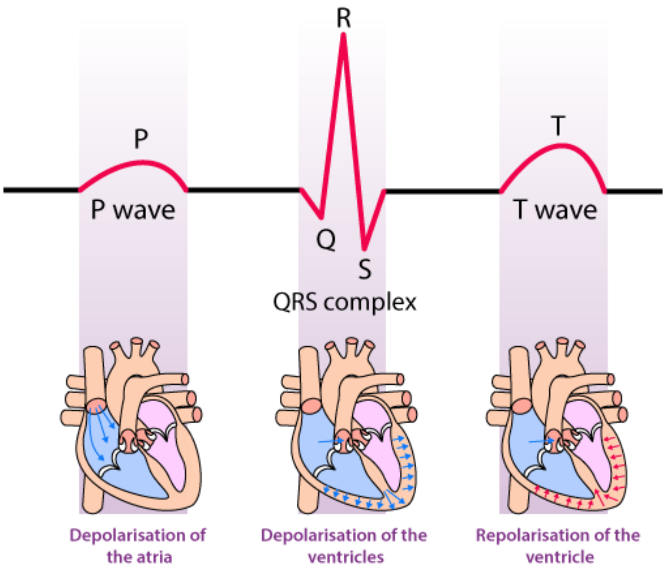

Fig. 1: The PQRST waves of the ECG signal correspond to the mechanics of the heart.

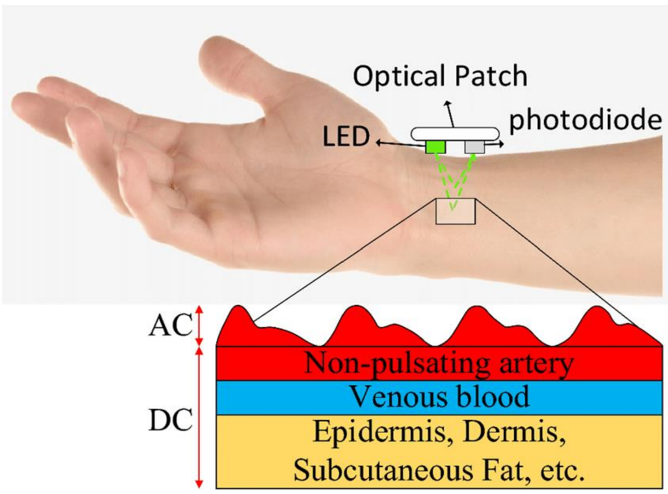

Fig. 2: Light emitting diode (LED) and a photodetector is used in a PPG sensor for the measurement of blood volume changes.

The difference between the PPG systolic peak and the ECG R-wave refers to the pulse transit time, or PTT, which is the time it takes for the pulse to arrive at the wrist [7] (Fig. 3). According to Jingyu Choi, et al., blood pressure can be calculated from PTT [8] (Eq. 1).

$$BP = \frac{1}{0.7}\left(\frac{1}{2}\rho\frac{d^2}{PTT^2} + \rho g h\right) \quad (1)$$

where d is the approximate height of the patient, ρ is the average blood density, 1035 $\frac{kg}{m^3}$, h is the height difference between the individual's heart and their wrist and g is the gravitational constant. The patient or doctor can input these measurements into the watch, and the microcontroller within the watch would be able to use the PTT measurement to calculate the patient's blood pressure.

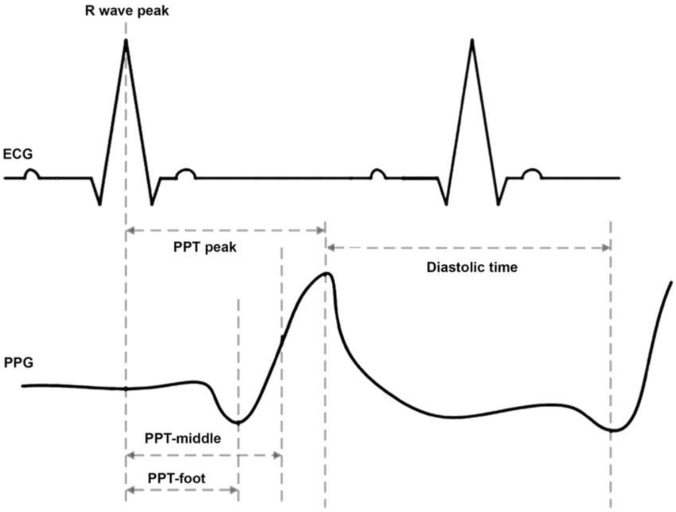

Fig. 3: PTT is the difference in time between the peaks of (top) ECG waveform and (bottom) PPG waveform.

The goal of this wearable device is to ensure both patients and doctors can constantly be aware of the patient's blood pressure. This is especially useful for the individuals who may suffer from or be at risk of hypertension, as doctors can react swiftly to an increase in blood pressure, potentially saving the patient from further, life-threatening complications.

2. INSTRUMENTATION DESIGN

2.1 Assumptions

In our circuit design, we have the following assumptions. (A) All input variables follow the pattern seen in an average hypertensive patients. (B) The tolerance for all resistors is 1%, while the tolerance for all capacitors is 5%. (C) Tested samples follow a simplified hypertensive case, with a systolic pressure between 140-190 mmHg and a diastolic pressure above 90 mmHg [2]. (D) The PPG signal of the tested point (the wrist) is representative of the body. (E) The signals from the sensors are uniform waveforms. (F) ECG output signal ranges between 0.5-5 mV [9]. (G) Threshold for pulse transit time (PTT) is <80ms for hypertensive patients (Eq. 1). (H) The two 555 timers behave identically and will turn off at the same time. (I) The maximum time difference between ECG and PPG peaks is 110 ms (Eq. 1). (J) Average heart rate is 80 beats per minute (bpm). (K) The time difference between systolic wave peaks is 350 ms. (L) The AC voltage source was modeled with a quasi-sinusoidal 1.4 Hz waves to simplify analysis and to replicate the frequencies of hypertensive in-patients' average resting heart rates of $83bpm\left(\frac{1min}{60s}\right) = 1.4Hz$ [10].

2.2 Overall Design

The overall circuit schematic is shown in Fig. 4. The circuit consists of three parts. Part I is the PPG circuit (top branch) which consists of six components: PPG sensor, inverting amplifier, buffer #1, passive RC low-pass filter, hysteretic comparator #1, and monostable 555 timer #2.

Part II is the ECG circuit (bottom branch) with the following six components: ECG sensors, instrumentation amplifier, buffer #2, passive RC high-pass filter, hysteretic comparator #2, and monostable 555 timer #2.

Part III is located on the right side of the graph, consisting of three components: XOR gate, microcontroller, and a display.

2.3 Breakdown of Circuit Analysis

2.3.1 Part I

2.3.1.1 Photoplethysmography (PPG) Sensor

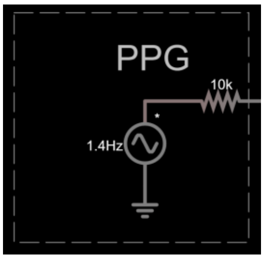

Fig. 5: PPG sensor

The first component in part I is the PPG sensor (Fig. 5), which provides the circuit with systolic and diastolic peaks at the wrist. assumptions. The input voltage, based on PPG wave properties, is supposed to be around 1V (arbitrarily selected). A resistor with the resistance value of $R_{in} = 10k\Omega$ is chosen.

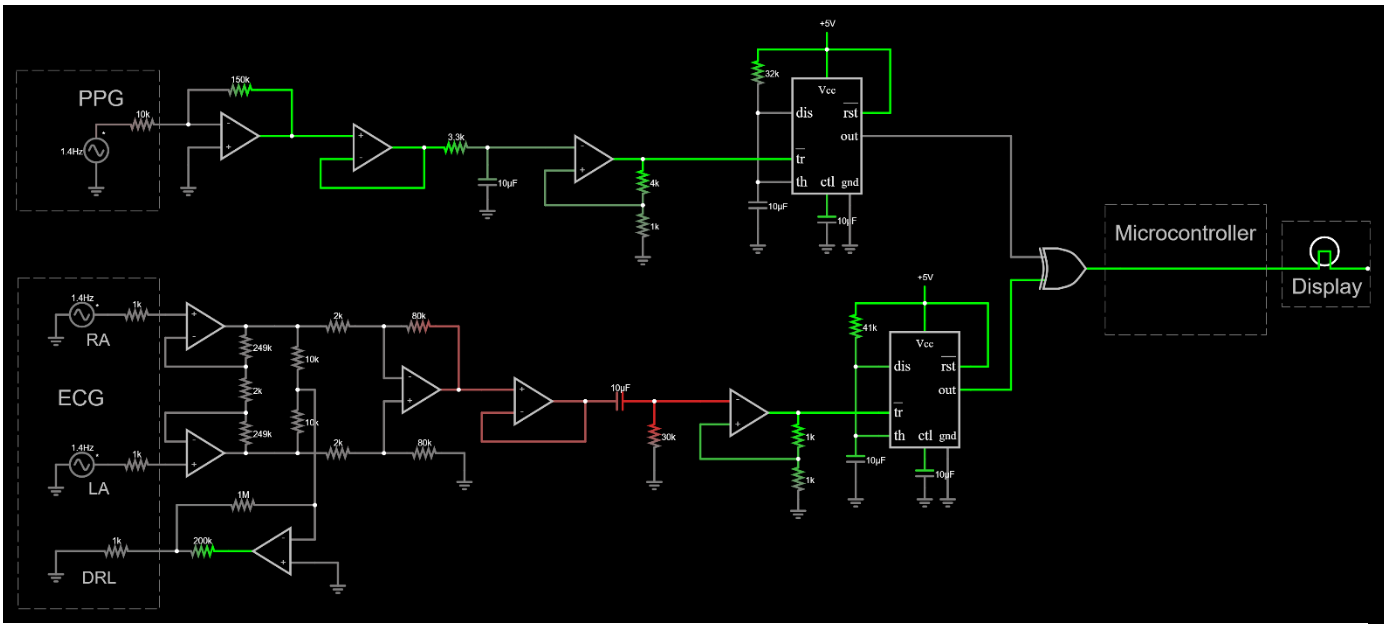

Fig. 4: Schematic of the overall circuit including PPG circuit, ECG circuit, and the microcontroller with the display. Created on Falstad.

The PPG input frequency is around 1.4 Hz, as calculated in the assumptions. The input voltage, based on PPG wave properties, is supposed to be around 1V (arbitrarily selected).

2.3.1.2 Inverting Amplifier

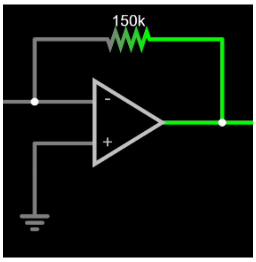

Fig. 6: *Inverting amplifier*

The second component, inverting amplifier, inverts and amplifies the input PPG signal, providing a negative gain (Fig. 6). The inverting amplifier consists of a feedback resistor $R_f = 150\ k\Omega$, an input $R_{in} = 10\ k\Omega$ and an amplifier. The V_{out} and gain is calculated to be $V_{out} = -10\ V$ and $A(Gain) = -10$, using (Eq. 2) and (Eq. 3) respectively below:

$$V_{out} = -\frac{R_f}{R_{in}} * V_{in} \tag{2}$$

$$A(Gain) = -\frac{R_f}{R_{in}} \tag{3}$$

2.3.1.3 Buffer #1

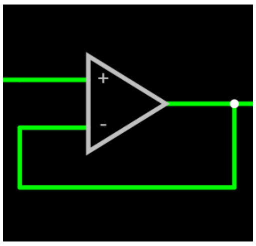

Fig. 7: Buffer #1

Buffer #1 isolates the previous and the next section of the circuit so that they do not affect each other (Fig. 7). Buffer provides a gain of 1 and $V_{out} = V_{in} = -10\ V$.

2.3.1.4 Passive RC Low-Pass Filter

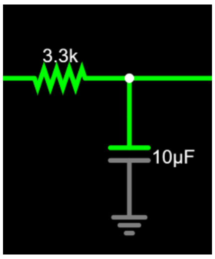

Fig. 8: Passive RC low-pass filter

PPG signal waves are low-frequency waves, and they may get contaminated by high frequency signals such as light. The low pass filter in part I filters the signal with a cutoff frequency of $f_c = 5\ Hz$ (Fig. 8). The cutoff frequency is chosen based on PPG wave properties, such that PPG waves of interest fall within the range of 0.5-5 Hz. A cutoff frequency at 5 Hz filters high frequency noises while preserving low frequency PPG signals. R_1 *and* C_1 are chosen based on (Eq. 4).

$$f_c = \frac{1}{2\pi RC} \tag{4}$$

Selected values based on formula: $R_1 = 3.3\ k\Omega$ *and* $C_1 = 10\ \mu F$. After the low pass filter, the signal frequency will be attenuated, allowing only low frequency PPG waves to pass. The output voltage V_{out} = 1.2 V.

2.3.1.5 Hysteretic Comparator #1

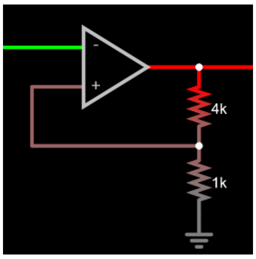

Fig. 9: Hysteretic comparator

The hysteretic comparator #1 compares the input PPG voltage with the default threshold V_{ref1} (Fig. 9), according to (Eq. 5) and (Eq. 6).

$$V_{in} < V_{ref1}, V_{out} = V+ \tag{5}$$

$$V_{in} > V_{ref1},\ V_{out} = V- \tag{6}$$

If the input PPG voltage is lower than the normal threshold PPG 1V, the output voltage will be 5V. On the other hand, if the input voltage is higher than the threshold PPG, the output will be GND. The two resistors have the values $R_{ref,GND}(bottom) = 1\ k\Omega$; $R_{ref,out}(top) = 4k\Omega$.

$$V_{ref1}+ = \frac{1}{1+4} * V+ = 1V$$

$$V_{ref1}- = \frac{1}{1+4} * V- = -1V$$

If the input voltage is higher than the threshold, $V_{out} = V+ = 5V$. If the input voltage is lower than the threshold, $V_{out} = V- = -5V$.

2.3.1.6 Monostable 555 Timer #1

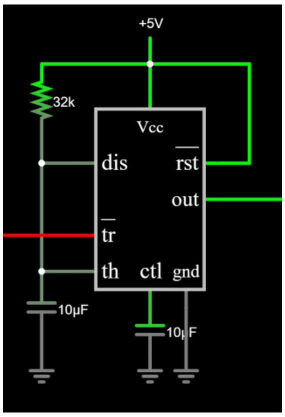

Fig. 10: 555 Monostable timer #1

A monostable 555 timer is used to capture the peak of the systolic peak on the PPG waveform. Based on PPG signal properties, the hold time interval of the monostable 555 timer T = 350 ms, which is selected arbitrarily to be less than the time interval between two consecutive R-waves of the ECG waveform (600 ms). Since we expect the PTT to be 110 ms at most and the PPG waveform to hit its peak after the R-wave of the ECG waveform, the T value of 350 ms makes the most sense for this device.

Based on (Eq. 7) , a set of values selected: $R = 32\ k\Omega$ and $C = 10\ \mu F$. During T, the output voltage of the timer is $V_{out} = V_{cc}$. However, after T, $V_{out} = 0\ V$ until timer #1 is triggered again by another output voltage from the comparator.

$$T = RCln(3) \tag{7}$$

2.3.2 Part II

2.3.2.1 Electrocardiogram (ECG) Sensors

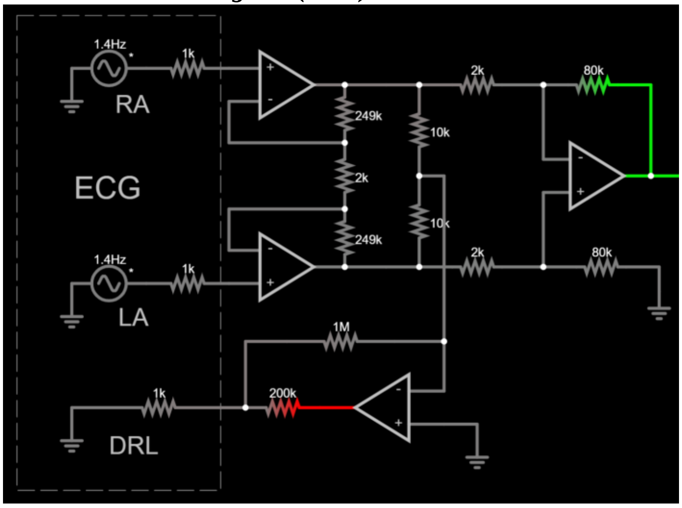

Fig. 11: Electrocardiogram (ECG) with bioinstrumentation amplifier and driven right leg (DRL) active grounding

The first component of part II is a single-lead ECG sensor that simulates true ECG voltage values ranging from 0.5-3 mV (Fig. 11). For this circuit, the AC voltage sources have input values of 2.5 mV and 3 mV for the top (RA) and the bottom (LA) electrodes, respectively.

2.3.2.2 Instrumentation Amplifier

The second component is a bioinstrumentation amplifier with various resistance values $R_o = 249\ k\Omega, R_a = R_3 = 2\ k\Omega,$ and $R_4 = 80\ k\Omega,$ while resistances for the arms' electrodes were chosen to have arbitrary resistance values as these are dependent on several external factors: $R_{RA} = R_{LA} = 1\ k\Omega$. Consequently, this amplifier is meant to achieve a differential gain of 10,000 using (Eq. 8) which is then multiplied by V_d from (Eq. 9) to give an amplified voltage output calculated with (Eq. 10).

$$A_d = \left|\left(1 + \frac{2R_o}{R_a}\right)\left(\frac{-R_4}{R_3}\right)\right| \quad (8)$$

$$V_d = V_{LA} - V_{RA} \quad (9)$$

$$V_{out} = V_d A_d \quad (10)$$

Based on the equations, it is computed that the voltage output is $V_{out} = (3-2.5)*10^{-3}V\left|(1+\frac{2(249k\Omega)}{2k\Omega})(\frac{-80k\Omega}{2k\Omega})\right| = 5V$, which is reasonably within the normal instrumental voltage ranges and is useful for outputting noticeable voltage in the later stages of part II.

A common mode rejection ratio (CMRR) for the instrumentation amplifier can be found using (Eq. 11) and (Eq. 12).

$$A_c = resistors * tolerance * \frac{R_4}{R_3} \quad (11)$$

$$CMRR_{dB} = 20\log_{10}\frac{A_d}{A_c} \quad (12)$$

Therefore, the circuit's common mode rejection ratio is $CMRR_{dB} = 20\log_{10}\left(\frac{\left(1+\frac{2(249k\Omega)}{2k\Omega}\right)}{4*0.01}\right) = 76\ dB$, which is not as high as the recommended $80\ dB$ to have a signal-to-noise (SNR) ratio greater than $40\ dB$. Resultantly, a driven right leg ground was also utilized to greatly reduce interference noise by directly lowering common mode voltage V_{cm} while also preventing too much current from entering the body due to the electrodes and circuitry.

$$V_{cm} = \frac{R_{RL} * i_d}{1 + \frac{R_{DRL,feedback}}{R_a}} \quad (13)$$

$$SNR_{in,dB} = \left|\frac{0.5 * V_d}{V_{cm}}\right| \quad (14)$$

$$SNR_{out,dB} = 6dB + CMRR_{dB} + SNR_{in,dB} \quad (15)$$

$$I_{source,max} = \frac{V_{source}}{R_{DRL,output}} \quad (16)$$

The resistance values chosen $R_{DRL,output} = 200\ k\Omega, R_{DRL,feedback} = 1\ M\Omega, R_a = 10\ k\Omega$ reflect the feedback gain found in (Eq. 13) to be $1 + \frac{R_{DRL,feedback}}{R_a} = \left(1 + \frac{1M\Omega}{10K\Omega}\right) = 101$ of the amplifier to reduce the V_{cm} by a factor greater than 100. The V_{cm} is calculated using (Eq. 13) to be $V_{cm} = \frac{100k\Omega*1\mu A}{101} = 1\ mV$, where typical values of the numerator are $R_{RL} = 100\ k\Omega$ and $i_d = 1\ \mu A$. Thus, based on (Eq. 14) and (Eq. 15), as $SNR_{in,dB} = \left|\frac{0.5*5*10^{-3}V}{1*10^{-3}V}\right| = -12dB$, the $SNR_{out,dB} = 6dB + CMRR_{dB} + SNR_{in,dB} = 6 + 76 - 12 = 70dB$ which is considered a strong SNR.

Additionally, as a 3V battery is being used for the device, $V^+ = 1.5\ V$ and $V^- = -1.5\ V$. Therefore, the current that may run through the driven right leg can be calculated using (Eq. 16) where $I_{source,max} = \frac{1.5\ V}{200\ k\Omega} = 7.5\ \mu A$, which is below the safety maximum of $10\mu A$ entering the body.

2.3.2.3 Buffer #2

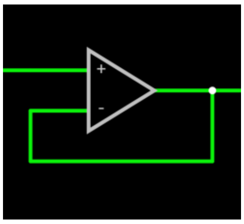

Fig. 12: Buffer #2

The buffer component of part II, like part I, prevents any current or signals from leaking into the previous stages (Fig. 12). Additionally, its gain is equal to 1 to prevent any incoming signal attenuation or amplification.

2.3.2.4 Passive RC High-pass Filter

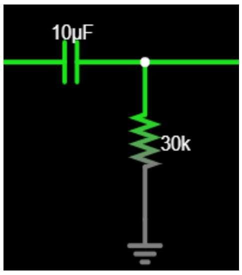

Fig 13. Schematic of high-pass filter

A passive RC high-pass filter is employed to remove any unwanted frequencies below $0.5\ Hz$ such as baseline wander, interference noise which occurs from external factors such as skin-electrode impedance and patient's movement [11] (Fig. 13). Therefore, a resistance of $R = 30\ k\Omega$ and a capacitance of $C = 10\ \mu F$ are used to obtain the cutoff frequency f_c based on (Eq. 4), similar to the calculation for the RC low-pass filter.

2.3.2.5 Hysteretic Comparator #2

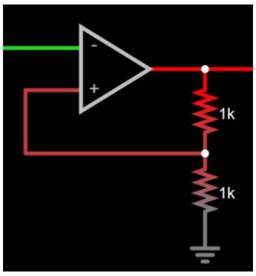

Fig 14. Hysteretic comparator #2

Part II also uses a hysteretic comparator for the sole reason of converting the sine waves into square waves for less noise interference and a more stable trigger signal when entering the next monostable 555 timer (Fig. 14). Square waves are desired because they oscillate between only two values – high and low – rather than the range of voltage values for a normal sine wave. Therefore, like part I, two resistors of $R = 1k\Omega$ in a hysteretic comparator offer two voltage output values $V_{out} = +5V$ if $V_{in} < 2.5V$ and $V_{out} = -5V$ if $V_{in} > 2.5V$ where $2.5V$ refers to the voltage threshold calculated using the voltage divider equation listed as (Eq. 17). In the case of this circuit, the only voltage outputs that will be utilized are when $V_{out} = -5V$ if $V_{in} > 2.5V$ because the monostable 555 timer can only take in negative inputs for it to be triggered.

$$V_{th} = \frac{R_1}{R_1 + R_2} V_{output} \tag{17}$$

2.3.2.6 Monostable 555 Timer #2

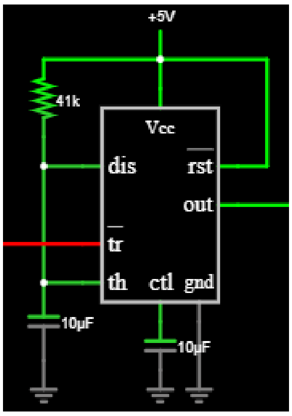

Fig 15. Monostable 555 timer #2

The last component of part II is another monostable 555 timer with a period of $T = 450ms = 1.1 * 41k\Omega * 10\mu F$ (Fig. 15). This period was chosen because the typical time delay between two R-waves of a resting heart rate measured by an ECG can be averaged to a value of $600\,ms$. Therefore, to ensure the PTT of ~$110\,ms$ is achieved without another R-wave signal interfering, a period of $450\,ms$ is used in conjunction with the $350ms$ period from the PPG.

2.3.2 Part III

2.3.3.1 XOR Gate

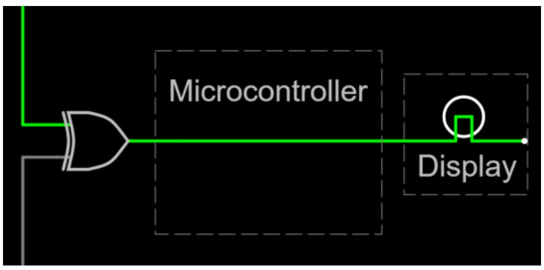

Fig. 16: XOR gate (left), microcontroller (middle), and digital display (right)

Part III consolidates the output signal from monostable 555 timer #1 of the PPG circuit (Part I) and the monostable 555 timer of the ECG circuit (Part II). The XOR gate is incorporated as a way of indirectly measuring the time delay between the ECG and PPG timers (Fig. 16). The XOR gate takes in the voltage outputs from the two timers and produces a digital binary output. It returns "true", or 1, if and only if one of the timers is outputting a voltage. For example, if the ECG timer sends a signal while the PPG timer is not outputting anything, then the XOR gate will output a "true", or 1. However, if both timers output voltages simultaneously, then the XOR gate will return a "false", or 0. An example truth table is shown in (Table 1).

TABLE I. XOR GATE TRUTH TABLE

Timer #1	Timer #2	XOR Gate Output
1	0	1
0	1	1
1	1	0
0	0	0

Only the "true", or 1, output from the XOR gate will feed into the microcontroller for further processing and calculation of blood pressure from PTT. For clarification, the time delay between the R-wave peak of the ECG waveform and the systolic peak of the PPG waveform is the pulse transit time (PTT).

2.3.3.2 Microcontroller with Blood Pressure Calculator

The use of a microcontroller in part III is for the processing of the signal received from the XOR gate (Fig. 16). As shown in (Fig. 17), the microcontroller is powered by a power supply and functions through an algorithm in the form of a code that is stored in the read-only memory (ROM). The code is sent to the central processing unit (CPU) for the processing of the input signal.

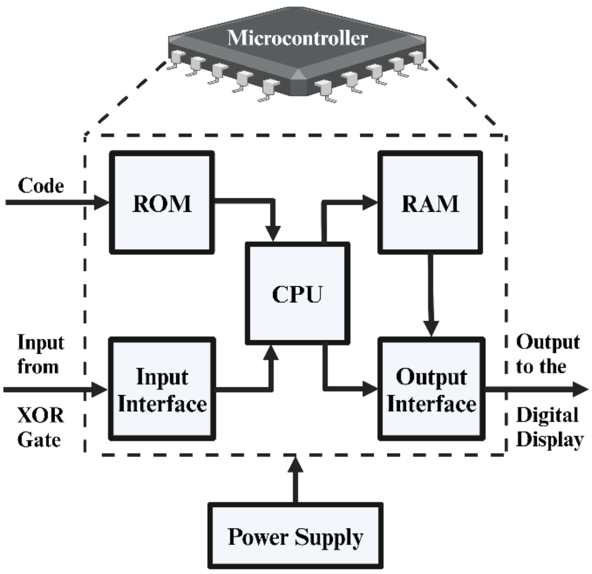

Fig. 17: Schematic to show components inside the microcontroller. Created with Biorender.

The built-in code basically assigns the microcontroller to record how long the XOR gate is activated for. This time interval is the input of the microcontroller from the XOR gate that goes through the input interface before reaching the CPU. Because the time period of the XOR gate "true" output signal is equivalent to the PTT, the microcontroller can indirectly measure PTT from the ECG timer and the PPG timer. Subsequently, it will calculate blood pressure of the patient from PTT using (Eq. 1). The computed blood pressure will be sent to the random access memory (RAM) for temporary storage of the data. Meanwhile, the CPU will also compare this computer blood pressure to the threshold that is indicative of hypertension, specifically blood pressure values above 140 mmHg. If the blood pressure is higher than this threshold, then the value stored in the RAM is immediately sent to the output interface for the sending of further signal/warning to the digital display.

2.3.3.3 Digital Display

The digital display is the last component of Part III (Fig. 16). Finally, once the output from the microcontroller is sent to the display, it will show the blood pressure on the screen of the wearable watch-like device. If the blood pressure of the patient is higher than 140 mmHg, the display will show a warning that the patient has hypertension and signify that they need to take medication or require immediate medical treatment.

3. RESULTS

3.1 Relationship Between BP and PTT

The relationship between blood pressure (BP) and pulse transit time (PTT) is shown in (Eq. 1). It shows that blood pressure has a mathematical relationship with ρ, d, PTT, g and h. Among the values from the equation, PTT is the only value constantly changing as it is dependent on the R-wave and the systolic peak, which have variable values depending on the patient. Thus, a qualitative relationship can be drawn that BP and PTT are inversely related. If PTT is low, blood pressure will be high (hypertension), and vice versa is true.

3.2 Output Voltage from Monostable 555 Timers

To obtain the value of the PTT, the time difference between the systolic peak of the PPG waveform and the ECG R-wave is measured indirectly by the output of the XOR gate, which is the input into the microcontroller.

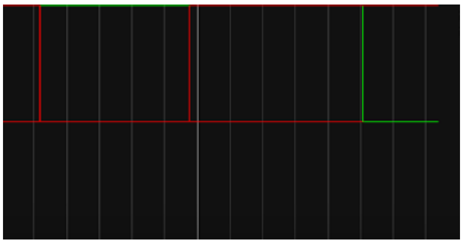

Fig. 18: Voltage output (green) from timer #2 hooked up to ECG sensors and voltage output (red) from timer #1 hooked up to PPG sensor.

As seen from the two waveforms, the time difference between the leading peak of PPG and leading peak of the ECG is around 110ms. This time differential of 100ms is the PTT, which corresponds to a normal blood pressure of 103 mmHg, using (Eq. 1), assuming a length of 0.7 meters from the wrist to heart and a height of 1.7 meters.

3.3 Waveform Components

The naturally-occurring time delay between ECG and PPG waveforms is shown in (Fig. 19). This delay can be taken advantage of to measure the pulse transit time (PTT), which is a metric for the calculation of blood pressure. In the ECG waveform (blue wave), the time difference between the two consecutive R-waves of the ECG waveform is roughly 600 ms. Once the ECG triggers the timer, the XOR gate would immediately get activated. When the PPG waveform (green wave) reaches its systolic peak, its timer is triggered, deactivating the XOR gate from sending the signal to the microcontroller. In a healthy human, the signal that the XOR gate sends to the microcontroller will be less than 110 ms based on calculations with (Eq. 1). Therefore, a PTT of 100 ms typically corresponds to normal blood pressure while PTT below 80 ms correlates to the blood pressure of a patient who has hypertension. Because of this range of PTT that the device operates on, it can be used for patients who are either healthy but are at risk of hypertension or in-patients who need their blood pressure monitored all the time in a hospital setting.

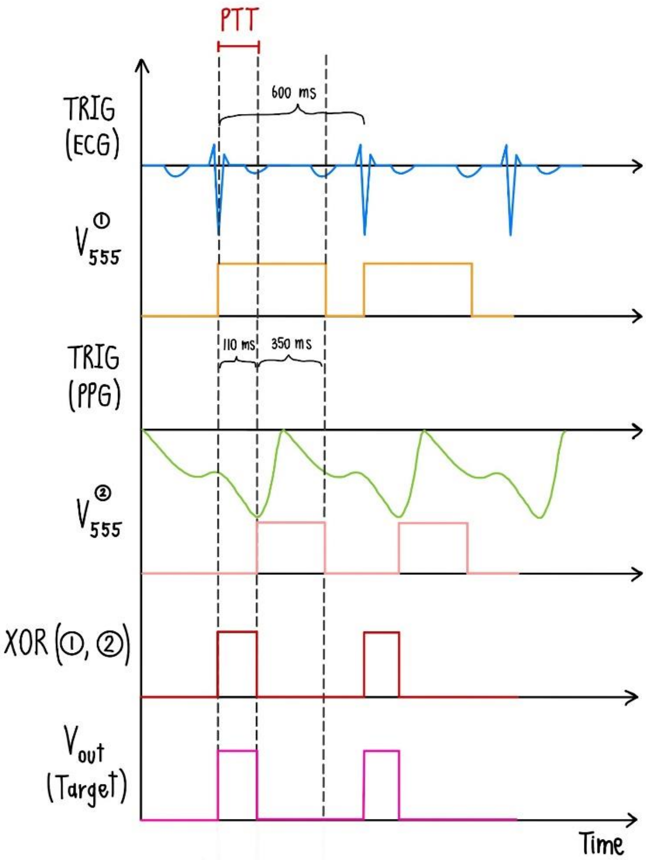

Fig. 19: PTT of around 110 ms between R-wave of ECG waveform (blue) and systolic peak of PPG waveform (green).The output voltage of the ECG timer (yellow) and PPG timer (light pink). The trigger of the XOR gate (red), as well as its output (pink).

4. DISCUSSION

4.1 Significance of Results

Upon testing on a non-hypertensive patient (referring to section 3.2 of results section), the device validates our proposed design choice of picking to include both ECG and PPG sensors. The simultaneous utilization of the sensors enables overarching monitoring to boost reliability. The circuit we designed demonstrated that for an upper PTT limit of 110 ms, there will be a blood pressure output of 103 mmHg, which is within the average healthy blood pressure range. This illustrates the idea that measuring blood pressure for a hypertensive patient, one with a PTT of <80 ms is possible, as the input PPG and ECG signals would differ from the ones in our circuit diagram.

4.2 Advantages of Device

The primary advantage of utilizing a dual sensor system, comprising PPG and ECG, is the non-invasive measurement of blood pressure. As previously noted, PPG-ECG data collection involves the collection of data from the patient's body through two separate parts of the body: the wrist and the chest. This innovative way of measuring blood pressure reduces the discomfort that may be experienced by patients. In contrast to traditional blood pressure measuring devices that are wrapped around the arm with inflatable cuffs, the sensors are light on the body, and come in the form of wearable devices alongside patches to measure ECG. Inflatable cuffs on the other hand require patients to be in stationary setups that require movements from patients, which can be taxing to patients. The innovative technology of the microcontroller will create a patient-friendly interface that is easy to follow and utilize.

4.3 Limitations and Future Considerations

Currently, our dual-sensor device is only applicable in medical settings as the ECG leads must be constantly worn by patients to get fully accurate data. In order to overcome the difficulties of restricting our product to medical situations, we will be designing it with everyday usability in mind in the future. Another thing that needs improving is the accuracy of the pressure readings. Due to the physiological factors, signals often show fluctuations in the blood pressure readings. To overcome this obstacle, the microcontroller can be leveraged to process signals at a precise rate. Our goal is to direct our product towards everyday and medical patients who suffer from hypertension to get the most accurate results.

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