Systolic Blood Pressure Estimation Using Video Processing

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***Abstract*—It is important to have access to a blood pressure monitor at home for regular blood pressure checking, especially for patients with cardiovascular diseases. In this study, we develop a low-cost and convenient blood pressure measurement method that can potentially be used for in-home health monitoring. Our proposed method uses only a smart phone's built-in camera and microphone. The proposed framework records acoustic and visual signals and extract principal biomedical features to estimate pressure values. This paper mainly focuses on obtaining the pulse transit time and estimate systolic blood pressure. Via video processing, we extract the pulse waves of two different locations on the body (neck and wrist) and obtain the timing delay between these two signals. We then perform linear regression analysis to examine the correlation between the pulse transit time and systolic pressure. When evaluated on nine healthy subjects, the experimental results report that the pulse transit time obtained from the video correlates with the systolic pressure. Combining these results with the pulse pressure obtained from audio processing, we are able to estimate both systolic and diastolic pressure.**

Keywords: blood pressure measurement, non-invasive, pulse transit time, carotid pulse, radial pulse

I. Introduction

High blood pressures put patients at higher risk for serious health problems such as heart disease, kidney failures, and strokes. However, high blood pressure usually gives no signs or symptoms [1]. Therefore, it is important to measure blood pressure regularly for early diagnosis and treatments of hypertension. The traditional cuff method of measuring blood pressure is inconvenient and the discomfort during the inflation and deflation of the cuff may increase the patients stress level, which subsequently affects accurate readings. Therefore, many non-invasive measurement devices are developed. However, most of them are expensive and require using special sensors such as Ballistocardiogram (BCG) or Photoplethysmogram (PPG) [2].

The ultimate goal of our study is to develop a low-cost and convenient method of blood pressure measurement system, which involves using only a smart phone and can be done easily at home. Our approach includes two parts: obtaining the pulse pressure from audio processing and systolic pressure from video processing. Pulse pressure is the difference between the systolic and diastolic pressure readings. From the pulse pressure and systolic pressure, we can acquire the diastolic pressure. This paper mainly discusses about how we obtain the systolic pressure.

II. Background

Blood pressure is the pressure of the blood in the circulatory system. It is comprised of systolic pressure and diastolic pressure. Systolic pressure indicates the force of blood in arteries as the heart contracts and pushes blood through arteries to the rest of the body. Diastolic pressure indicates the force of blood in arteries as the heart relaxes between beats [3]. This paper focuses on how to deduce the systolic pressure.

Pulse Transit Time (PTT) is the time it takes the pulse pressure wave to propagate through a length of the arterial tree [4]. Many studies have shown that PTT is a good indicator of systolic pressure [5][6][7]. In this paper, PTT refers to the difference between the PTT from heart to wrist and the PTT from heart to neck.

III. Method

Our method takes a video that captures the subject's wrist and neck simultaneously and extracts features from these locations and perform feature tracking across all frames in the video. After Principle Component Analysis (PCA) decomposition, we obtain the carotid pulse waves (pulse signals of neck) and radial pulse waves (pulse signals of wrist). From these pulse signals, we calculate the PTT by subtracting pulse peak locations of the neck from the wrist. Finally, we perform linear regression to deduce systolic pressure.

A. Feature Tracking

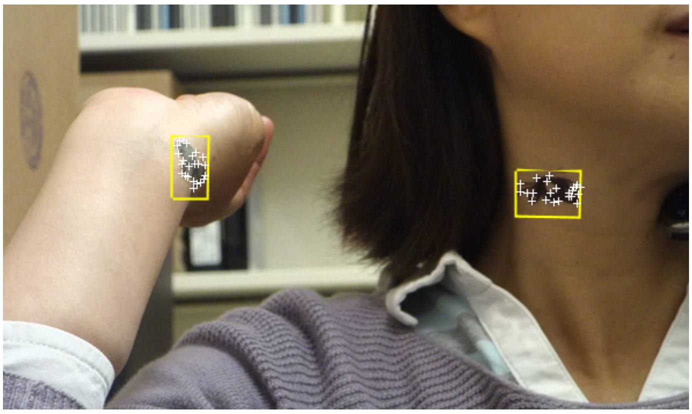

Fig. 1: Sample recording with feature points extracted.

To extract features more easily, temporary tattoos are applied to the subject's neck and wrist where the pulse feels the strongest. Temporary tattoos can be quickly removed afterward. Since the videos can be recorded at different angles and positions, we select the regions of interest where the temporary tattoos are located. For each location, we extract the strongest 25 feature points using minimum eigenvalue algorithm [8].

These feature points are tracked across each frame in the video using the Kanade-Lucas-Tomasi tracking algorithm [9]. Figure 2 plots the magnitude changes in x and y directions of 25 feature points on the neck across all frames.

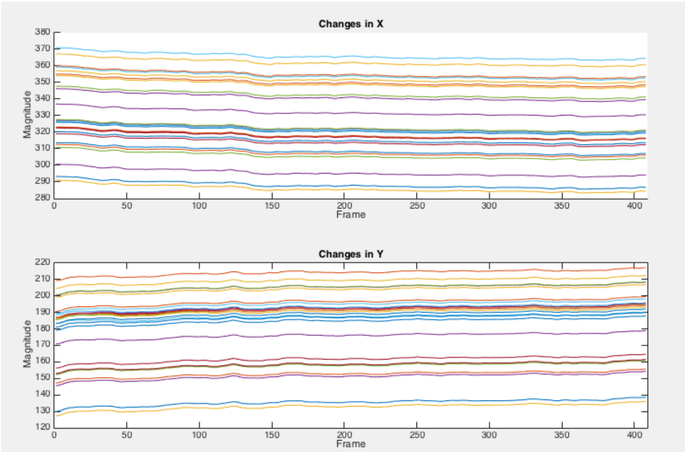

Fig. 2: Plot represents changes in magnitudes of feature points in X and Y directions over time.

B. Temporal Filtering

To reduce the negative effects of signals such as respiration or large movements in postures, we apply butterworth filter to retain only signals that are within the range of human heart rate as shown in Fig. 3. We choose the range from 0.75 to 5Hz, which proved to produce good pulse detection [10].

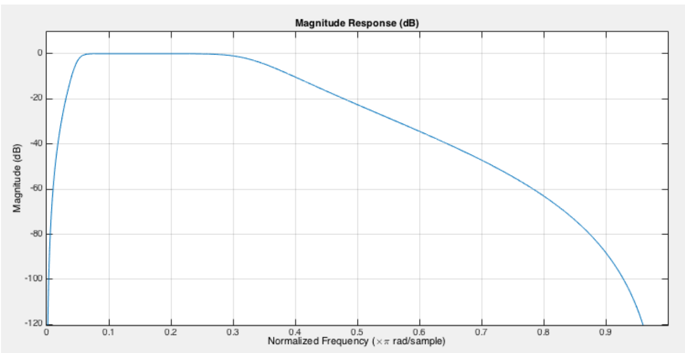

Fig. 3: Magnitude response of temporal filter with a pass-band [0.75 - 5] Hz.

We want to take into account the magnitude changes in both x and y directions. Because the magnitude changes are recorded in x and y separately, we combine the x and y signals at each frame by taking the norm of (x,y):

$$xy(t) = \sqrt{x(t)^2 + y(t)^2}$$

Additionally, since the sampling rate of regular smart phone cameras are only around 30 Hz, we interpolate the signals using spline interpolation.

C. PCA Decomposition

We represent the position of N feature points across M frames as a matrix of size $N \times M$.

Let $s_n(t)$ denote the neck signals at frame t and $s_w(t)$ denote the wrist signals at frame t. For each type of signals, we calculate the mean vector, which contains the mean value of each feature points across M frames.

$$\overline{s_n} = \frac{1}{M}\sum_{t=1}^{M} s_n(t)$$

$$\overline{s_w} = \frac{1}{M}\sum_{t=1}^{M} s_w(t)$$

The covariance matrix can be found by:

$$\Sigma_{s_n} = \frac{1}{M-1}(s_n - \overline{s_n})(s_n - \overline{s_n})^T$$

$$\Sigma_{s_w} = \frac{1}{M-1}(s_w - \overline{s_w})(s_w - \overline{s_w})^T$$

We perform PCA decomposition on the covariance matrix using the PCA function in Matlab, which produces the coefficients matrix where each column is the coefficients for one principal component. Figure 4 and 5 depict the cartoid signals and the radial signals obtained by projecting the signals onto the first principle component, respectively.

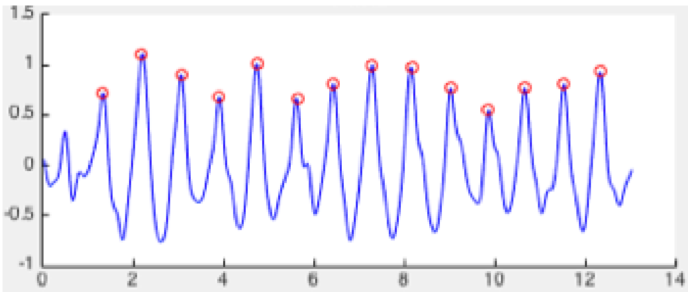

Fig. 4: Carotid signals obtained after PCA.

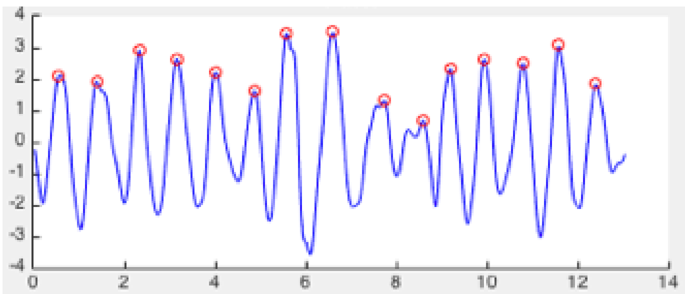

Fig. 5: Radial signals obtained after PCA.

D. Calculating PTT

We perform peak detection on the two pulse waves obtained after PCA (as shown in Fig.4 and Fig.5). The peak locations are stored to compute the PTT, as described in the following pseudocode:

Algorithm 1 PTT Computation Algorithm

procedure FINDPTT
  $neckIdx \leftarrow 1$
  $wristIdx \leftarrow 1$
  $sumPtt \leftarrow 0$
  $count \leftarrow 0$
  while $wristIdx \leq length(wristPeaks)$ & $neckIdx \leq length(neckPeaks)$ **do**
    if $wristPeaks[wristIdx] \leq neckPeaks[neckIdx]$ **then**
      $wristIdx \leftarrow wristIdx + 1.$
    else
      $ptt = (wristPeaks[wristIdx] - neckPeaks[neckIdx]) \times \frac{1000}{FrameRate}$
      if $low \leq ptt$ & $ptt \leq high$ **then**
        $sumPtt \leftarrow sumPtt + ptt$
        $count \leftarrow count + 1$
        $wristIdx \leftarrow wristIdx + 1$
        $neckIdx \leftarrow neckIdx + 1.$
      else
        $neckIdx \leftarrow neckIdx + 1.$
  return $sumPtt/count$

We add the threshold since the peak locations are sometimes off and do not match up, which result in unreasonably small or large values of PTT. After applying this function, we inspect the results to detect and eliminate any abnormal matches between the neck and wrist peaks.

E. Validation and Linear Regression

We verify the neck and wrist pulse frequency obtained from the video against the heart rate recorded from the blood pressure monitor. The measured heart rate of the subject in Fig. 4 and Fig. 5 is 69 bpm. The pulse frequency of the carotid signals is 14 $peaks/12\ seconds = 1.167$, which yields a heart rate of 70 bpm. The pulse frequency of the radial signals is 15 peaks/13 seconds = 1.153, which yields a heart rate of 69 bpm. The accuracy rate in this case is more than 98%.

In order to verify that the neck pulse peaks are correct, we can also perform audio recording to obtain the carotid sounds and heart sounds. Audio recording is done simultaneously while video recording the subject. The neck signals are recorded by placing a regular phone's microphone on the subject's neck. The heart signals are recorded by placing the stethoscope on the subject's chest. The stethoscope is connected to a mini microphone, which is plugged into to the computer to record the heart signals. Both devices begin and end recording at the same time. The signals are synchronized afterward. Figure 7 shows the heart signals and neck signals of a sample recording. The neck pulse peaks can be validated by aligning the pulse waves with the heart and neck sound as illustrated in Fig. 6 [11].

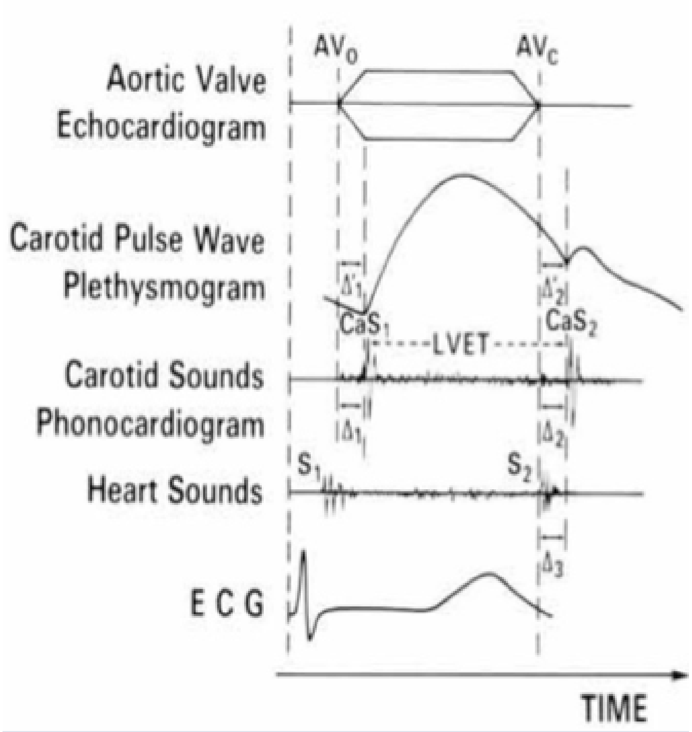

Fig. 6: Carotid pulse waves and corresponding carotid sounds and heart sound [11].

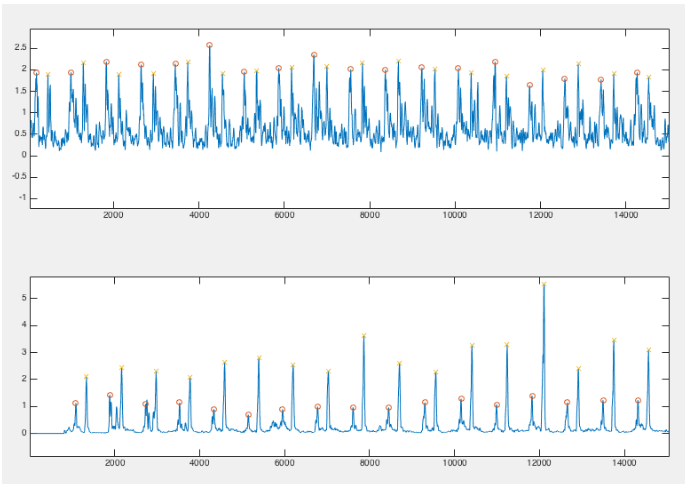

Fig. 7: Heart and neck signals obtained from audio recording. Top figure is the recorded heart sounds and bottom figure is the recorded carotid sounds.

From the measured systolic pressure and the PTT, we examine the relation between the two parameters by performing simple linear regression analysis. We collect 19 data points across 9 different healthy subjects. We discuss the results in

Section V. Using the function from linear regression, we can estimate the systolic pressure.

IV. Measurement Protocal

Recordings are done in a quiet environment and after the subject is seated at rest for at least 5 minutes. Video recording and audio recording are done simultaneously as illustrated in Fig. 8.

A. Video Recording

1) Apply temporary tattoos to the neck and wrist. Tattoos should be placed at the location where the pulse feels the strongest. The strongest neck pulse is typically on the side of the neck and below the jaw. The strongest wrist pulse is usually located on the inside of the wrist near the side of the thumb.
2) The subject sits still and refrains from moving as much as possible while being recorded. It is helpful to place the arm on a sturdy surface where the wrist is positioned near the neck.
3) Place the camera on a tripod such that it captures both the neck and the wrist.
4) Record for about 15 seconds.
5) Measure heart rate, systolic, and diastolic blood pressure using a wrist digital blood pressure. Record the values.

B. Audio Recording

1) Place the recording device on the neck and apply a steady pressure to the area with the microphone.
2) Find the location on the chest with the strongest pulse. The strongest heartbeat is typically towards the center-left of the chest or on top of the bottom left ribs. Use a belt to secure the stethoscope in place. The heart sound is recorded from a computer by connecting the stethoscope to a mini microphone.
3) Begin the recording on the phone and the computer as the video recording starts.
4) After about 15 seconds, tap the phone and the stethoscope together for at least three times to create a large sound. This sound is used for synchronization afterward.
5) Stop the recording and measure the blood pressure. Record the values.

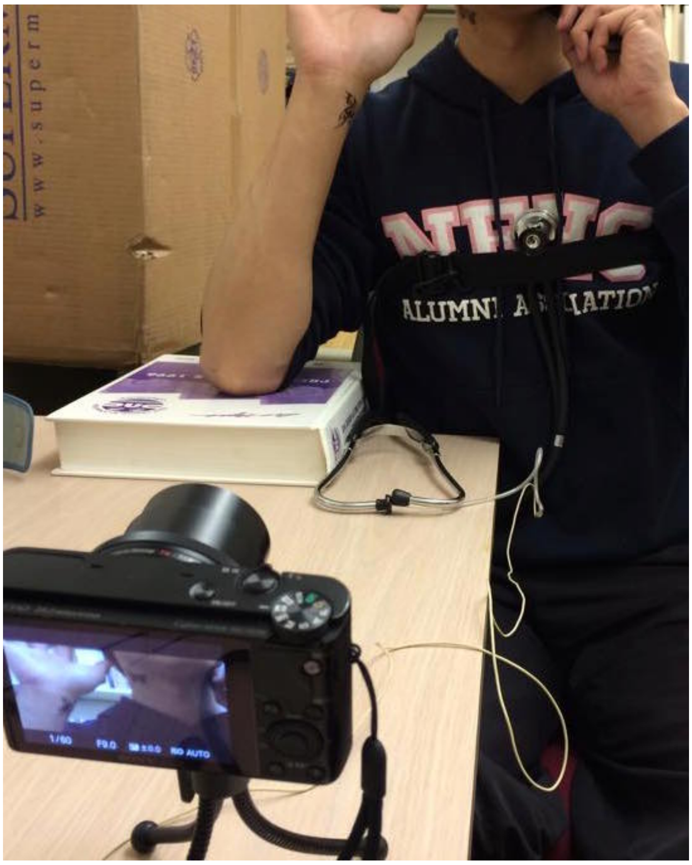

Fig. 8: Subject being recorded.

SP(mmHg)	PTT(ms)
100	36.11
101	40.28
95	44.44
93	51.39
111	52.22
92	46.67
82	60.00
103	60.00
106	41.67
108	30.56
111	47.22
114	33.33
133	38.89
118	52.22
120	40.28
120	56.67
93	50.79
94	61.11
91	77.78

TABLE I: Measured Systolic Pressure and PTT

V. Results and discussion

We measure the blood pressure and obtain the PTT from 19 data points and perform simple linear regression. Our subjects include 6 males and 3 females. The subjects average age is 33 with a std of 12.53, average height is 173.6 cm with a std of 9.2 and average weight is 71 kg with a std of 13.75. Recordings are done at different time of day for three weeks. Table I shows the collected data.

After obtaining the PTT, we perform linear regression to examine the relation between the measured systolic pressure and PTT. Figure 9 shows the relation between the two parameters with the formula included in the plot. The correlation coefficient is 0.4263. As seen from the graph, the higher the PTT, the lower the pressure, which is consistent with previous studies [5][6][7][12].

Using the function from linear regression, we can predict the systolic pressure for future recordings from the PTT. Figure 10 illustrates the plot of actual versus predicted systolic pressure.

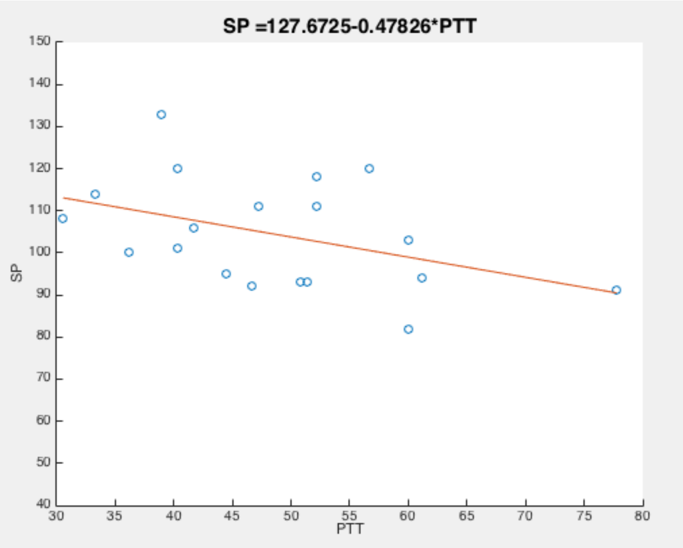

Fig. 9: Plot of the relation between Systolic Pressure and PTT. The straight line represents linear regression (see inserted formula).

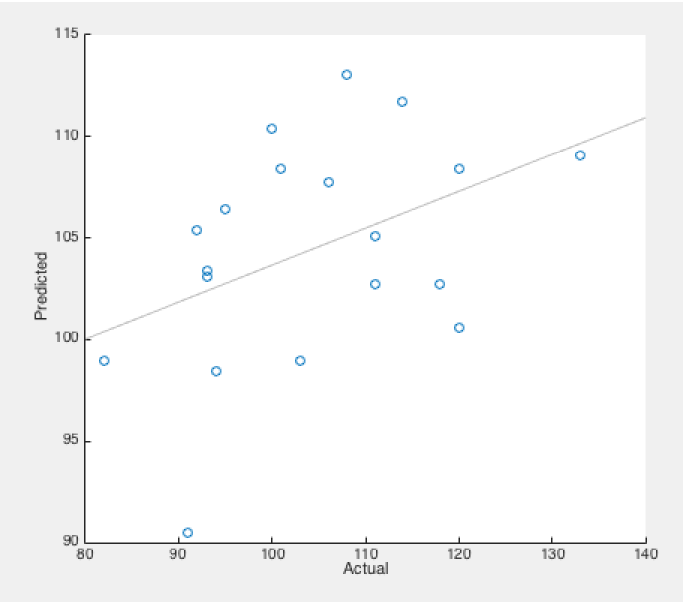

Fig. 10: Plot of Actual vs. Predicted Systolic Pressure.

It is possible to obtain better results using Pulse Wave Velocity (PWV) since PTT does not take into account the length of the arterial tree. Therefore, PTT is more suitable for intra-subject instead of inter-subject regression analysis. Additionally, because of heart rate variation, it is better to use a continuous monitor to produce more accurate readings. In the future, other parameters such as body surface area (BSA), the difference between two heart sounds, and the left ventricular ejection time (LVET) from audio processing can be utilized to produce better systolic pressure estimations.

VI. Conclusions and Future Work

This paper presents a low-cost and convenient method to estimate systolic pressure using video processing. Our method extracts pulse transit time between the neck and the wrist. Using the PTT, we perform linear regression to estimate systolic blood pressure. By incorporating the systolic pressure from video processing and the other biomedical features from audio processing, we can estimate both systolic and diastolic blood pressure. The method can be useful in self blood pressure monitoring at home or clinical diagnosis in health care.

In the future, we want to collect more data for better regression analysis. Additionally, our feature extraction algorithm currently requires the subject to apply temporary tattoos. Another feature extraction algorithm is desirable so that enough feature points can be extracted without the help of temporary tattoos. We also wish to examine the relationship between the harmonics in the power spectrum and the blood pressure. During our experiments, we noticed that the carotid pulse signals are usually clear and consistent while the radial pulse signals sometimes consist a lot of noise and unusual peaks. This is expected since the movements of neck arteries are easily visible by the human eyes while the movements of pulse in the wrist are not apparent. The unusual peaks most likely come from posture changes or arm movements. To overcome this, we can perform color variation on the wrist region instead of motion tracking. This would most likely yield a much clearer radial pulse signals.

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