Bangladesh University of Engineering and Technology

EEE 312: Digital Signal Processing 1 Laboratory

Project Name: ECG, PPG & PCG based Estimation of Blood Pressure

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Abstract:

This paper presents a novel blood pressure (BP) estimation method based on pulse transit time (PTT) and pulse arrival time (PAT) to estimate the systolic BP (SBP) and the diastolic BP (DBP). A data acquisition hardware is designed for high-resolution sampling of phonocardiogram (PCG), photoplethysmogram(PPG), and electrocardiogram (ECG). PCG and ECG perform as the proximal timing reference to obtain PTT and PAT indices, respectively. In order to derive a BP estimator model, a calibration procedure, including a supervised physical exercise, is conducted for each individual, which causes changes in their BP, and then, a number of reference BPs are measured alongside the acquisition of the signals per subject. It is suggested to use a force-sensing resistor that is placed under the cuff of the BP reference device to mark the exact moments of reference BP measurements, which are corresponding to the inflation of the cuff. Additionally, a novel BP estimator nonlinear model, based on the theory of elastic tubes, is introduced to estimate the BP using PTT/PAT values precisely. The proposed method is evaluated on 32 subjects. Some non-linear model has been run to compare between the prediction level.

Keywords— Force Sensing Resistor(FSR), Pulse arrival time (PAT), Pulse transit time (PTT), Preejection period (PEP).

Background:

A. Relationship Between BP and PTT

The key principle behind using PWV for BP estimation is that the blood flow in the arteries can be modeled as the propagation of pressure waves inside elastic tubes. Specifically, by assuming vessels such as elastic tubes, elastic modulus (E) of the vessel walls can be written as

$$E = E_0 e^{\alpha(P-P_0)}$$

where P is the fluid pressure (here BP), and E0, P0, and α are individual-specific parameters. The compliance (C) is defined as the rate at which the tube cross section changes in terms of P. Considering the conservation of mass and momentum equations, it can be seen that C is a function of P.

$$C(P) = \frac{A_m}{\pi P_1 \left[1 + \left(\frac{P-P_0}{P_1}\right)^2\right]}$$

where P0, P1, and Am are individual-specific parameters. Writing the wave propagation equations inside the vessels, which are assumed as elastic tubes, leads to the following equation:

$$P(x,t) = f(x \pm t/\sqrt{LC(P)})$$

where L = ρ/A; in which, ρ and A are the blood density and the vessel cross section, respectively. Therefore, PTT for a tube of length l can be derived as

$$\mathrm{PTT} = \frac{l}{\mathrm{PWV}} = l\sqrt{LC(P)}.$$

Furthermore, by substituting L and C(P), PTT can also be formulated as

$$\mathrm{PTT} = l\sqrt{\frac{\rho A_m}{\pi A P_1\left[1+\left(\frac{P-P_0}{P_1}\right)^2\right]}}.$$

The PTT-BP relationship for each individual is described in with the aid of individual-specific parameters. l is related to the distance between the distal and proximal points at the time of PTT measurement. By solving for P (BP here), BP can be derived as a function of PTT

$$\mathrm{BP} = P_0 + \sqrt{-P_1^2 + \frac{l^2\rho A_m}{\pi A} \times \frac{1}{\mathrm{PTT}^2}}$$

which can be rewritten in a more simplified form as

$$\mathrm{BP} = a_0 + \sqrt{a_1 + a_2\frac{1}{\mathrm{PTT}^2}}$$

B. PTT/PAT Measurement Method

Corresponding PTT/PAT to each pair of proximal and distal time instances is measured by the calculation of distal time minus proximal time. In this paper, PCG S1-peak is considered as the proximal timing reference to measure PTT as it approximately represents the moment that BP wave leaves the heart. S1 and S2 are two dominant types of sounds in the PCG signal, where S1 corresponds to the closure of mitral and tricuspid valves, while S2 corresponds to the closure of aortic and pulmonary valves. Also, similar to many research studies in the literature, ECG R-peak is considered as the proximal timing reference for measuring PAT.

A characteristic point on the PPG, in the same cardiac cycle as the selected proximal timing reference, is considered as the distal timing reference. This point could be either the point where PPG begins to rise in each cardiac cycle (PPG f), the point where the PPG slope reaches its maximum (PPGd), or the systolic peak of PPG (PPGp), where the PPG itself reaches its maximum. The corresponding PAT/PTT values are called PATf , PATd, and PATp, and PTTf, PTTd, and PTTp, respectively.

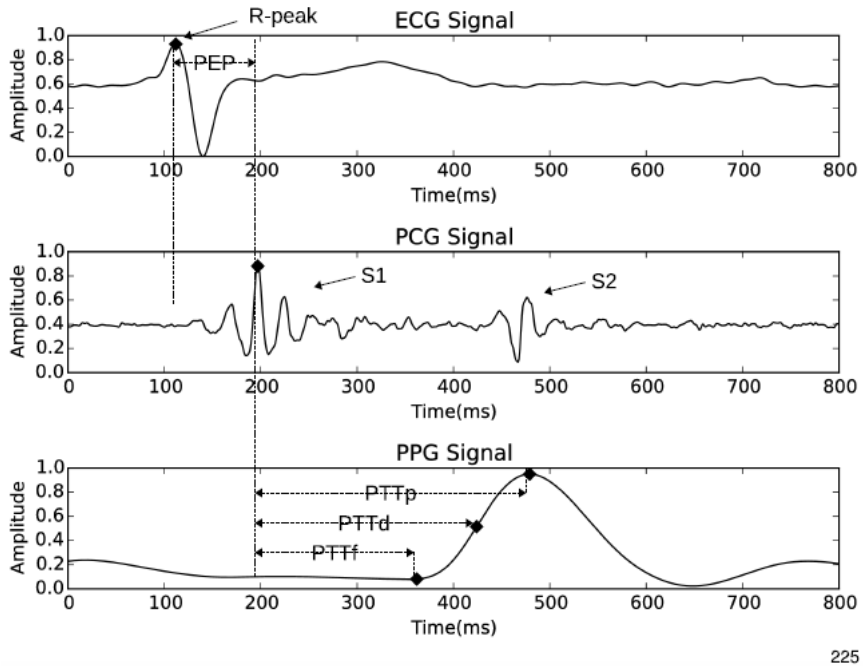

Fig: PTTp, PTTd, PTTf, PEP shown in the ECG, PPG & PCG signal.

Processing:

A. Preprocessing on the Signals

For preprocessing on the signals, first, all four signals are smoothed using the median filter technique to reduce the impulsive noise effect. As the median filtering is a nonlinear technique, the employed window width is limited to a sample (approximately 5000). Next, all the signals are statically normalized. At the end, frequency filtering is performed on the signals. For frequency filtering, Savitzky–Golay filters, which are more computational efficient than butterworth filters, are used. In particular, for the FSR signal, because of the relatively long time intervals between reference BP measurements, a low-pass filter is exploited. For the rest

of the signals, bandpass filtering is used. The pre-processing specifications for each of the acquired signals in the data collection process are shown in the table below.

Signal	Outliers Removing	Baseline Wandering	Moving Average	Low Pass Filter
FSR	√		√	√
ECG	√	√	√	√
PPG	√		√	√
PCG	√		√	√

B. PTT/PAT Measurement and Postprocessing

At the beginning, the three main signals (i.e., PCG, PPG, and ECG) are divided to time intervals, where each interval corresponds to one of the BP measurements by the automatic BP monitor. There are three key moments in each reference BP measurement:

1) when the cuff begins to inflate (t1)
2) when the cuff begins to deflate (t2)
3) when cuff deflation finishes and SBP and DBP values

are measured and read by the automatic BP monitor (t3). The FSR signal can distinguish these three moments, since it represents instantaneous applied pressure by the cuff. The t3 moments are used to divide the main signals to the mentioned time intervals.

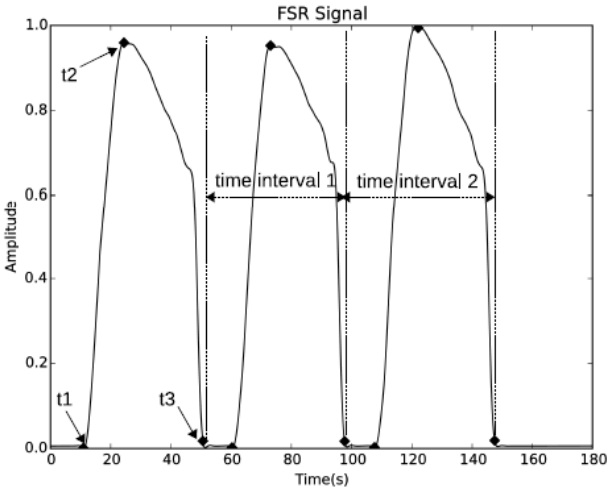

Fig: Time windowing of FSR (BP measurement points).

PTT and PAT values corresponding to each of reference BP measurements are calculated from corresponding time intervals.

For PTT/PAT measurement in each time window, the main signals should be delineated reliably. To determine the ECG R-peak and distinguish it from other peak types in ECG, the ECG itself and its first derivative are analyzed simultaneously. As the R-peak is more isolated than other peak types in ECG, the value of the first derivative of ECG is higher near the R-peak position (see Fig. 6). Accordingly, we applied a threshold of about 0.9 on the normalized ECG signal to find a few R-peak candidates, and then, we used the value of derivatives before and after each candidate to select the R-peak. For delineating PCG, however, the fact that S2-peak is closer than S1-peak to PPGp in each cardiac cycle can be employed to distinguish S1-peak from S2-peak (see Fig. 7). Therefore, after finding a few candidate points for S1 and S2 peaks, we used their relative positions to the PPG systolic peak to decide on S1 and S2 assignments. PPG f , PPGd , and PPGp are determined through their definitions. Afterward, PTT/PAT values corresponding to each of these distal points are measured. It is worth mentioning that, in each time window, if the proximal or distal points cannot be delineated reliably, that specific window is excluded from our analysis. At last, the average of the extracted PTT/PAT values from time windows in each time interval is used to give one PAT value and one PTT value for that time interval. The obtained PTT average and PAT average in each time interval is corresponding to the reference BP measurement performed in that time interval. Doing this for all time intervals in data collection for each subject, we obtain reference BPs and associated PAT/PTT values for each subject. Using these pairs, the parameters in (7) can be approximated for each individual.

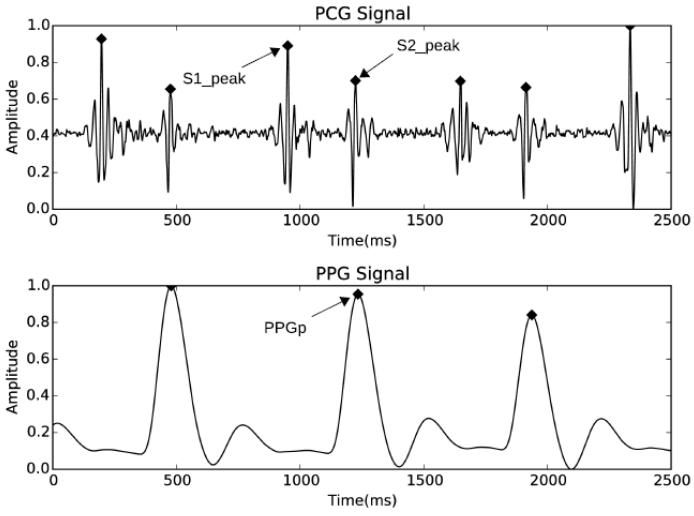

Fig: S1-peak is distinguished from S2-peak with the help of PPG.

C. Regression Model & Result

For basic purpose random forest regression has been applied in this project. Random forests or random decision forests are an ensemble learning method for classification, regression and other tasks, that operate by constructing a multitude of decision trees at training time and outputting the class that is the mode of the classes (classification) or mean prediction (regression) of the individual trees. Random decision forests correct for decision trees' habit of overfitting to their training set. The test score was 0.5358. Some of the test run has been shown below.

Actual SBP Value	Predicted SBP value
141.164	135
148.492	153
132.988	121
135.508	142
135.776	131

This result is not that much good. As we have used a dataset of just 16 rows, this doesn't train the model well. In future work, this problem will be resolved.

Acknowledgement:

- Dataset Used from Kaggle.com, provided by Mohammad Kachuee, University of California
  https://www.kaggle.com/mkachuee/noninvasivebp

- Papers has been studied primarily
  - Nonlinear Cuffless Blood Pressure Estimation of Healthy Subjects Using Pulse Transit Time and Arrival Time
    http://ieeexplore.ieee.org/abstract/document/8032000/
  - Cuff-less high-accuracy calibration-free blood pressure estimation using pulse transit time
    http://ieeexplore.ieee.org/abstract/document/7168806/