WAVELET-BASED ADAPTIVE KALMAN FILTERING FOR BLOOD PRESSURE ESTIMATION VIA FUSION OF PULSE ARRIVAL TIMES

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PERSPECTIVE

Motivations

- Hypertension, or High Blood Pressure (a medical condition in which arteries are experiencing a persistently elevated blood Pressure), is the cause for at least 45% deaths due to heart disease, and 51% of deaths due to stroke.
- Continuous Blood Pressure measurements are great means of retrieving invaluable information about subjects' health conditions in order to prevent, detect, evaluate, and early start of treatment of hypertension: Recent urgency to design continuous and cuff-less blood pressure monitoring solutions.

Objectives

- Pulse Arrival Time (PAT), defined as the time for the pulse to travel from the heart to a peripheral site, is able to perform BP measurements non-invasively and continuously, because a significant correlation exists between the BP and the PAT.
- We seek for a novel wavelet-based feature extraction algorithm coupled with an adaptive and multiple-model Kalman filtering framework.

PROPOSED ALGORITHM

Contributions of the Proposed Algorithm

- Accurate and simple, needless of an a priori threshold for R-peak detection
- Adaptive and multiple model Kalman Filter framework for BP estimation based on PPG and ECG feature extraction
- High quality, high SNR signal acquisition by Gen-1
- Highly accurate R-peak detection algorithm based on Wavelet Transform analysis

Step-by-Step

ECG and PPG Data Acquisition by **Gen-1** & Pre-Processing to filter out the noise

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ECG Feature Extraction
Wavelet Transform and R-Peak detection

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PPG Feature Extraction
(i) The on-set of the PPG,
(ii) The peak of the PPG, and,
(iii)The peak of the derivative of each PPG cycle i.e, the maximum slope-point (MSP) of each PPG cycle

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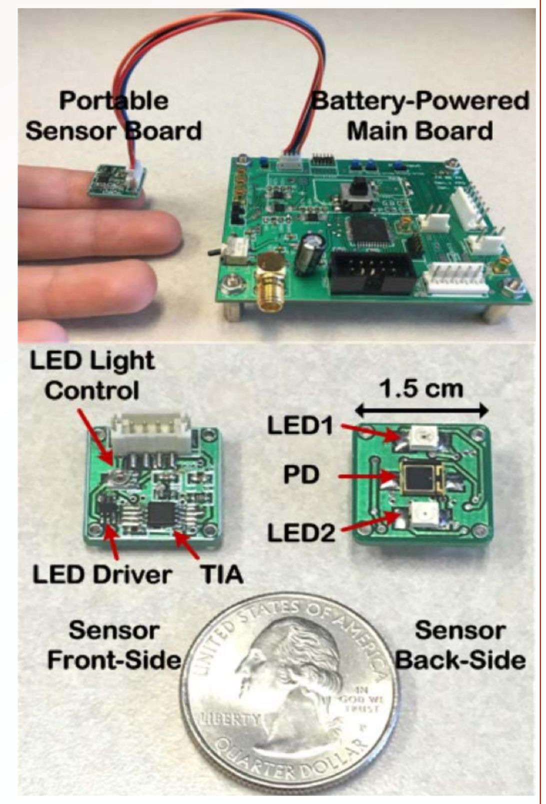
BP Estimation based on KF via Three Models

$$\text{Model 1:} \quad \mathrm{BP} = \alpha_1 \ln(\mathrm{PAT}) + \beta_1$$
$$\text{Model 2:} \quad \mathrm{BP} = \alpha_2 \mathrm{PAT} + \beta_2$$
$$\text{Model 3:} \quad \mathrm{BP} = \frac{\alpha_3}{\mathrm{PAT}^2} + \beta_3,$$

DATA ACQUISITION & PRE-PROCESSING

ECG Data Recording and Filtration

- The clinical bandwidth of ECG Signal: between 0.05-100 Hz.
- The signal is recorded at various sampling rates starting from 200Hz.
  To bring uniformity to the processing approach of ECG signals recorded at different sampling rates, the signal is re-sampled at 1KHz.
- The signal is decomposed using DWT by selecting the Biorthogonal 6.8 wavelet (bior6.8) as the mother wavelet function.



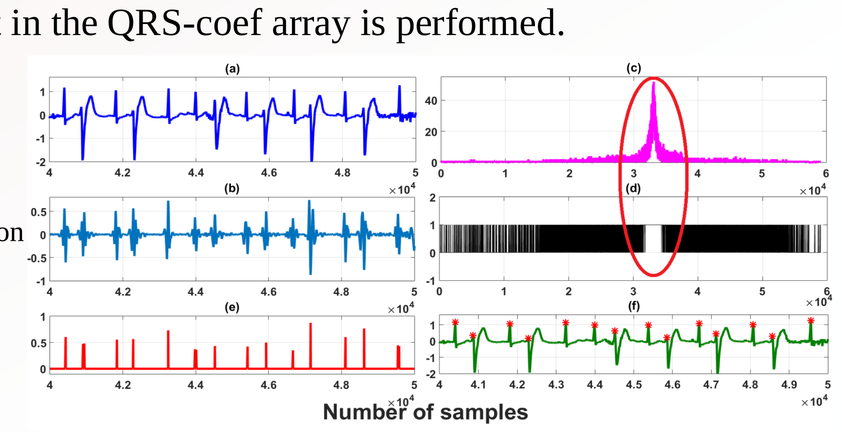
PPG Data Recording and Filtration

- The clinical signatures of PPG signal reside below 25 Hz.
- The signal is recorded at different sampling rates starting from 50Hz.
  PPG signal is also re-sampled at 1 KHz due to the same reason as in the case of ECG.
- The DWT-based signal denoising Technique (also used for ECG) is used for PPG, selecting the 'db8' wavelet function from the Daubechie's wavelet family.

PPG & ECG FEATURE EXTRACTION

A) R-Peak Detection

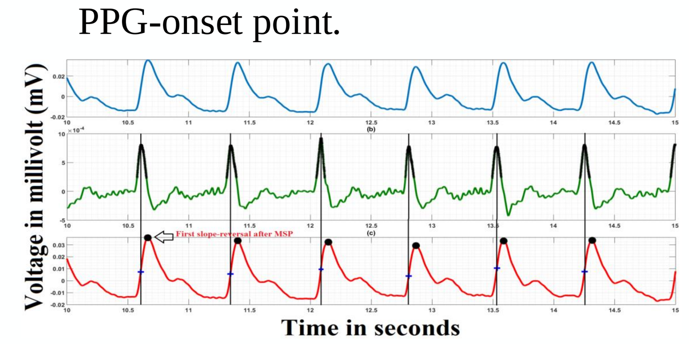
- An array (QRS-coef) is formed by adding the coefficients of the D4 and D5 (QRS-coef = D4 + D5).
- To boost the detection accuracy of the R-peak points, histogram analysis of the wavelet coefficients present in the QRS-coef array is performed.



(a) Denoised ECG
(b) *QRS-coef* data
(c) Histogram analysis of the *QRS-coef*
(d) Amplitude-band where the population of coefficients is Maximum
(e) Modified *QRS-coef* data
(f) Detected R-peaks

B) Fiducial-point Detection from PPG Signal

- First-derivative of the filtered PPG (FD-PPG) signal is calculated, and two different features are extracted from the FD-PPG signal: (1) maximum-slope-point (MSP) of every PPG cycle, and (2) systolic Peaks.
- Dividing systolic-peak intervals into 2:1 ratio, the mid-point of the peak-to-peak interval is calculated (M). Among all the samples in between every M-point and the immediate next MSP the maximum value of angle θ is found: PPG-onset point.



(a) Filtered PPG
(b) FD-PPG signal where marked samples are the ones within the threshold value
(c) Detected MSP and systolic-peaks

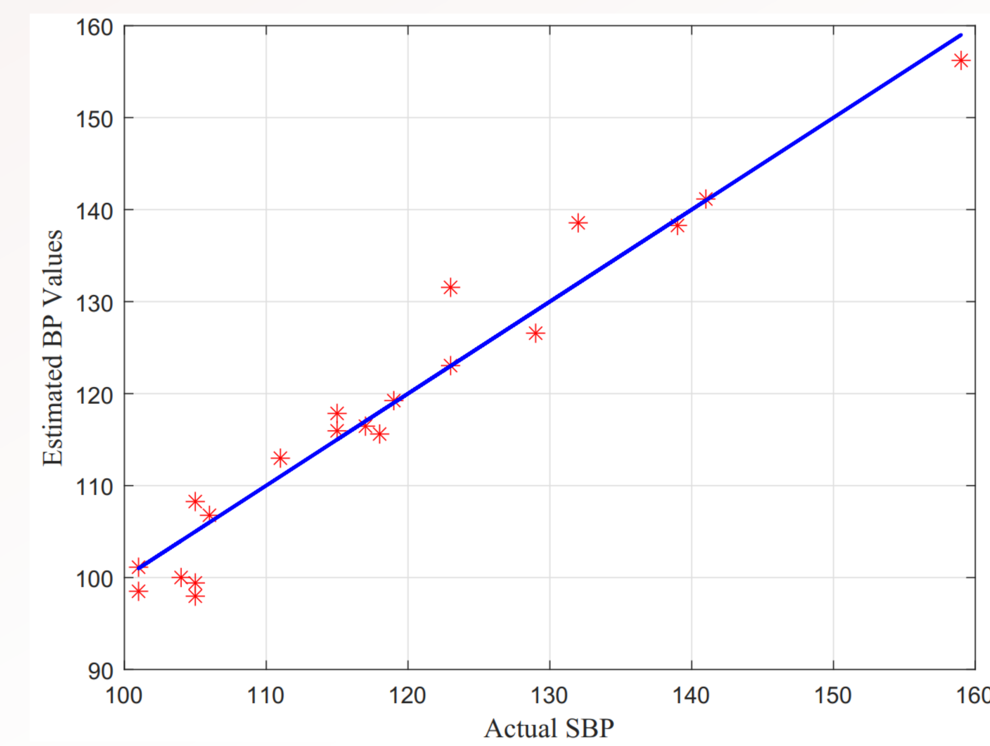
BP ESTIMATION & RESULTS

Kalman Filter-Based Algorithm

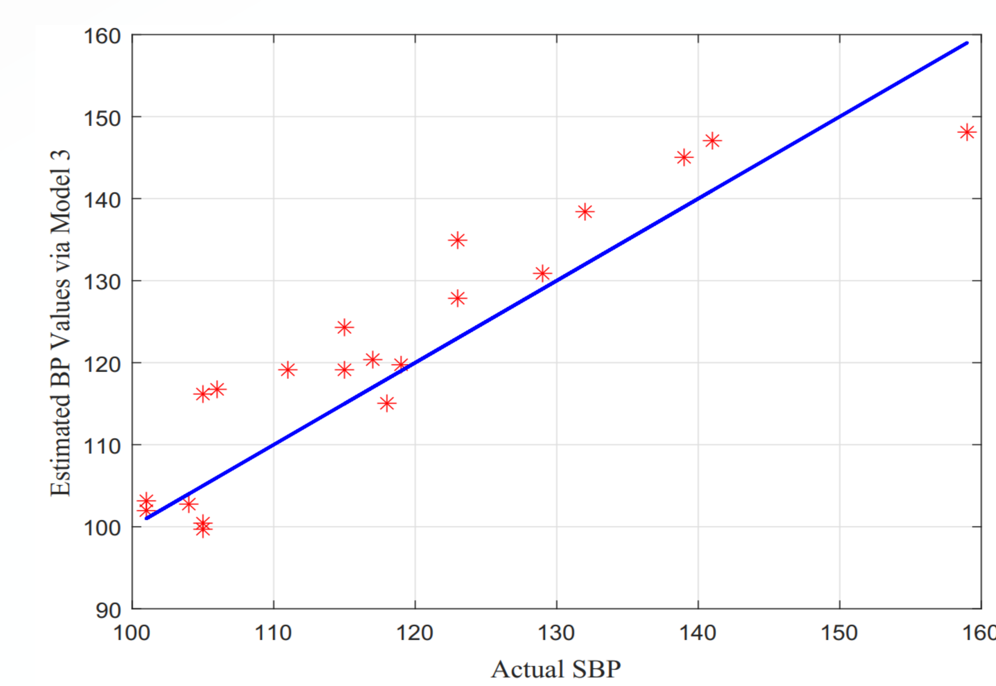
- An adaptive Kalman Filter for dynamical estimation, using a simple random walk to model BP evolutions over time an Autoregressive (AR) process of order p (in the experiments we used p=4).

$$\text{State Model:} \quad \mathrm{BP}(k) = \mathrm{BP}(k-1) + w(k)$$
$$\text{Observation Model:} \quad \ln \mathrm{PAT}(k) = \frac{1}{\alpha_1}\mathrm{BP}(k) - \frac{\beta_1}{\alpha_1} + v(k)$$

- We propose to use a bank (combination) of ($Nf > 1$) different observation models and construct a hybrid statespace model for recursive estimation of the BP (in the experiments we used $Nf = 2$ based on the two characteristic points of the PAT features).
- Experimental results Are presented based on a real data set collected from a healthy female volunteer. The BP variation is introduced by change in posture and exercise of the volunteer. The measured BP varied between 101 to 159 mmHg.
- 20 reference BP recordings are measured by a cuff-based Omron 10 device. The results obtained based on all 20 measurements with Point 5 with BP equal to 101 mmHg, and Point 6 with BP equal to 141 mmHg are used for calibration via the LS approach.



Based on the proposed WAKE-BPAT and Model 1



Estimated versus the actual BP Based on [2], i.e., Model 3

Statistics	WAKE-BPAT	Proposed Features via Model 1	Reference [1]	Reference [2]
Mean Error	**2.67**	3.47	4.46	4.32
Standard Deviation	**2.51**	2.79	6.05	5.46
RMSE	**3.62**	4.41	5.74	5.52

CONCLUSION

- We proposed a novel framework for non-invasive and continuous estimation of the blood pressure (BP) from Pulse Arrival Time (PAT), which provides accurate BP estimates by extraction/fusion of different PAT characteristics. The proposed WAKE-BPAT framework is evaluated based on a real data set.
- It is observed the proposed WAKE-BPAT framework outperforms its counterpart and the estimated BP values are fairly close to their actual ground truth, which attests to the effectiveness of the proposed cuff-less and continuous BP estimation framework.

REFERENCES

[1] Zheng, Y. L., Yan, B. P., Zhang, Y. T., & Poon, C. C. (2014). An Armband Wearable Device For Overnight And Cuff-less Blood Pressure Measurement. IEEE Transactions On Biomedical Engineering, 61(7), 2179-2186.

[2] Theodor, M., Ruh, D., Fiala, J., *et al*. (2013). Subcutaneous Blood Pressure Monitoring With An Implantable Optical Sensor. Biomedical Microdevices, 15(5), 811-820.

[3] Marefat, F., Erfani, R., Kilgore, K. L., & Mohseni, P. (2016, October). Minimally Invasive Muscle-based Recording Of Photoplethysmogram Toward Chronic Implantation. In Biomedical Circuits and Systems Conference (BioCAS), 2016 IEEE (pp. 388-391). IEEE.