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A Real-Time Maximum-Likelihood Heart-Rate Estimator for Wearable Textile Sensors

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***Abstract*— This paper presents a real-time maximum-likelihood heart-rate estimator for ECG data measured via wearable textile sensors. The ECG signals measured from wearable dry electrodes are notorious for its susceptibility to interference from the respiration or the motion of wearing person such that the signal quality may degrade dramatically. To overcome these obstacles, in the proposed heart-rate estimator we first employ the subspace approach to remove the wandering baseline, then use a simple nonlinear absolute operation to reduce the high-frequency noise contamination, and finally apply the maximum likelihood estimation technique for estimating the interval of R-R peaks. A parameter derived from the byproduct of maximum likelihood estimation is also proposed as an indicator for signal quality. To achieve the goal of real-time, we develop a simple adaptive algorithm from the numerical power method to realize the subspace filter and apply the fast-Fourier transform (FFT) technique for realization of the correlation technique such that the whole estimator can be implemented in an FPGA system. Experiments are performed to demonstrate the viability of the proposed system.**

I. INTRODUCTION

Since the world population is getting older and the demand of high quality of life is increasing, the need for a comfortably wearable system with capability to measure and wireless transmit vital signals is becoming more urgent [1]. The wearable sensors especially those made of textiles have been flourishing recently. For example, using the wearable medical clothes for monitoring respiration activity and ECG signal [2], for tele-home healthcare [3], for neurological rehabilitation [4] have been proposed recently. Extensive research effort for developing wearable medical devices has been immensely taken in the world such as the VTAMN project in France, the WEALTHY project in Europe, and the LifeShirt in USA [5]. We have developed a system in clothes [6] sewn with textile sensors capable of measuring vital signals such as the ECG, the respiration, and the body temperature, etc. The developed clothes is soft and comfortable and it is durable. In this paper, we focus on processing the received ECG data to estimate the heart-rate of the wearing person in real time because the heart rate and its variability (HRV) [7], [8] contain important physiological information. Since the steel textile electrodes are only in dry contact with the skin, the measured ECG signals, as well-known, are highly susceptible to interference caused by the motion of wearing person. The signals may exhibit high baseline wandering behavior and high noisy aberrations, making the heart-rate estimation from these measurements a nontrivial work. Moreover, the real-time requirement imposes further constraints on the work. To attain the goal, we first use the subspace technique for removing the wandering baseline and simple absolute operation to reduce high-frequency noise contamination. Then, the maximum likelihood technique is employed to estimate the heart-rate. To meet the real-time requirement, we develop a simple adaptive subspace filter and apply the fast-Fourier transform (FFT) for computing the correlation values required for maximum likelihood estimation technique. A signal-quality indicator is further presented to distinguish the usefulness of the measured ECG signals. Experiments for ECG data measured from the wearing person initially sitting still, then walking, and finally jogging, demonstrate the viability of the presented estimator.

II. THE WEARABLE SENSOR SYSTEM

The wearable sensor system in a shirt shown in Fig. 1 consists of one textile clothing knitted with vital sensors and a small control box used for signal integration, receiving, and transmission. The ECG sensor electrodes are made of steel textile sewn in the clothes such that the wearing person feels comfortable. The control box contains an amplifier, an anti-aliasing filter, and an analog-to-digital converter for the ECG signal; it also embeds a bluetooth transceiver for transmitting vital signals such as the ECG sensor data at the rate of 200 samples/sec to remote mobile phones or computers for post processing.

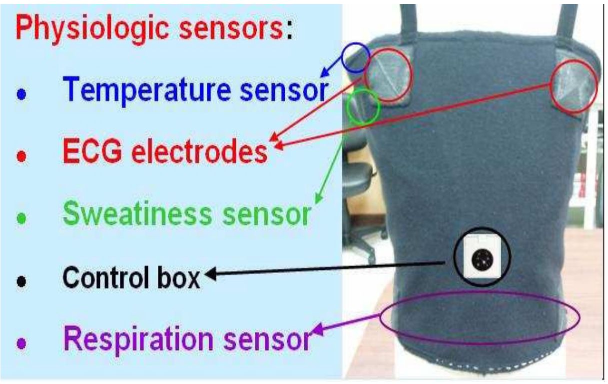

Fig. 1. The presented vital wearing sensor system

The receiver LabVIEW interface of the remote computer via bluetooth wireless transmission for typical measured data

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is shown in Fig. 2 where the two plots in center depict both the ECG and the respiration signals, the three meters on the lower left indicate the degree of sweatiness, the body temperature, and the room temperature, the three meters on the upper right show the three-axis accelerations of wearing person, and the pictured figure on the lower right illustrates the posture of the wearing person.

Fig. 2. The LabVIEW interface of the remote computer for typical measured data

III. THE REAL-TIME HEART-RATE ESTIMATOR

The block diagram of the proposed real-time heart-rate estimator is shown in Fig. 3. We use the subspace technique first to remove the wandering baseline in ECG signals. Then the simple absolute operation aims to reduce high-frequency noise. We finally apply the maximum-likelihood technique including evaluating the correlation and searching peak position for heart-rate estimation. We further propose a signal-quality indicator derived from the peak searching process to distinguish the usefulness of the ECG signals. Detailed description for each block is discussed below.

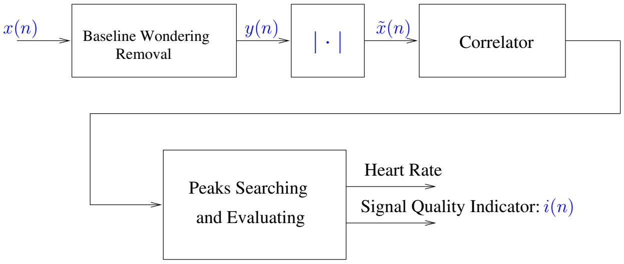

Fig. 3. The Proposed Maximum Likelihood Real-Time Heart-Rate Estimator

A. Adaptive Subspace Technique for Wandering Baseline Removal

The baseline wander in ECG signals is especially notorious in using the wearable dry electrodes because not only the respiration but also the motion of the wearing person make the baseline drift significantly. We observe from the experience on experiments that the subspace using only the eigenvector corresponding to the largest eigenvalue can characterize sufficiently the wandering baseline in most ECG signals. This choice of using one principal subspace further enables the real-time realization of subspace technique because a simple adaptive algorithm can be derived from the numerical power method [9]. We have discussed the developed procedure in [10]. Hence, we only list the adaptive algorithm in Table I to illustrate its simplicity.

TABLE I
ADAPTIVE SUBSPACE ALGORITHM USING POWER METHOD

Initialize: $\boldsymbol{q}(0) = [1, 0 \cdots 0]^T$; $\boldsymbol{p}(0) = \boldsymbol{0}; 0 \le \alpha \le 1$
For Each Time Step Do: $Input : \boldsymbol{x}(n)$ $\boldsymbol{p}(n) = \alpha \boldsymbol{p}(n-1) + (1-\alpha)\boldsymbol{x}^T(n)\boldsymbol{q}(n-1)\boldsymbol{x}(n)$ $\boldsymbol{q}(n) = \frac{\boldsymbol{p}(n)}{\|\boldsymbol{p}(n)\|}$ $\boldsymbol{b}(n) = \boldsymbol{q}(n)\boldsymbol{q}^T(n)\boldsymbol{x}(n)$: baseline wander $\boldsymbol{y}(n) = \boldsymbol{x}(n) - \boldsymbol{b}(n)$

B. Maximum-Likelihood Technique for Heart-Rate Estimation

This section discusses the developed heart-rate estimator and the signal-quality indicator. The heart rate is just the reciprocal of R-R interval in ECG signals within a specific time window. Hence it corresponds to the classic problem of frequency estimation [11]; assuming the contaminant noise is white, the maximum likelihood estimation algorithm turns out to evaluate the correlation values first and then search the position in which the peak value occurs. The correlation value for a shift length of m is defined below

$$c_r(m) = \sum_n \tilde{x}(n)\tilde{x}(n+m) \tag{1}$$

Thus, the correlation sums the product the original signal $\tilde{x}(n)$ and its shifted version $\tilde{x}(n+m)$. If the signal $\tilde{x}(n)$ is periodic, then when the shift length m equals the multiple of the signal period, we will obtain the peak correlation value.

As discussed above, the correlation peaks occur in every shift length equal to the multiple of signal period if the signal is perfectly periodic. If the signal quality degrades, the peaking effect will be reduced. This observation brings the development of a signal-quality indicator. We propose a signal indicator $i(n)$ as the ratio of the difference between the position of the second peak and the position of the first peak over the position of the first peak; that is

$$i(n) = \frac{\text{position of 2nd peak}(n) - \text{position of 1st peak}(n)}{\text{position of 1st peak}(n)} \tag{2}$$

Note that the index n is used in the indicator because for each sample the proposed estimator will compute one indicator value. When the value $i(n)$ is close to unity, the signal quality will be more reliable. If $i(n)$ is far from unity, then the signal shall be far from periodic and the heart-rate estimate for this signal should be treated in discreet. The experiment will demonstrate the usefulness of this indicator.

The realization for computing the correlation using (1) directly is computationally heavy and unsuitable for real-time processing. The correlation operation can be realized as the convolution because it can be shown that

$$C_r(e^{j\omega}) = \sum_m c_r(m)e^{-j\omega m} = \tilde{X}(e^{j\omega})\tilde{X}^*(e^{j\omega}) \qquad (3)$$

Hence, the computation of correlation can be realized via the FFT and inverse FFT (IFFT) operations; the block diagram of its realization is shown in Fig. 4. Finally, the positions of both the first peak and the second peak can be obtained by direct searching; simple manipulations will yield the resulting heart-rate estimate and the signal-quality indicator.

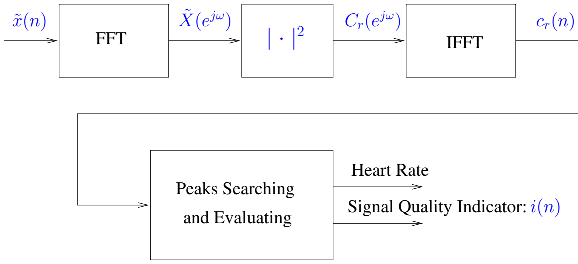

Fig. 4. The Algorithm for Realizing the Correlator

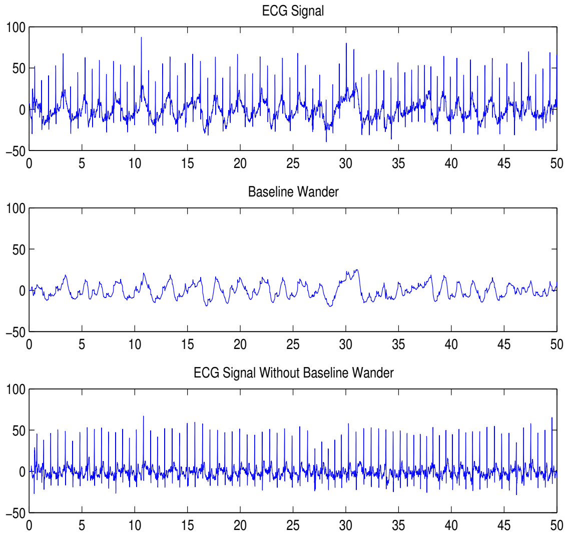

Fig. 5. The original ECG data, the estimated baseline aberration of adaptive subspace filter, and the final filter output.

C. Experiments

Three experiments are performed for measured ECG data with 8-bit resolution and sampling rate of 200 samples per second via the developed wearable sensor system to evaluate the proposed estimator. By experience, the vector length of adaptive subspace filter is set to 40. The adopted FFT length is 2048; thus the first estimate occurs after about 10 seconds. Afterwords, every new sample data will yield a new estimate and indicator. The first experiment demonstrates the effectiveness of the adaptive subspace wandering baseline removal. As shown in Fig. 5, the top first subfigure shows the original ECG data measured via the wearable sensors and the third subfigure depicts the output of the adaptive subspace filter. The second subfigure is the estimated baseline. As shown from these figures, the adaptive subspace technique successfully removes the baseline aberrations.

The second experiment shows the performance of proposed heart-rate estimator. The person wears the sensor shirt to ensure *tight* contact of the sensor electrodes on the skin. The wearing person is initially sitting still for about 30 seconds, then he stands up and walks at a regular pace for about one minute, and finally he starts jogging for near one minute. The measured ECG data are shown in the top first subfigure of Fig. 6. We see from the figure that the measured data contains erratic aberrations in the intervals of 34-42 and 98-108 seconds because of posture transitions of the wearing person. The output data after the baseline removal are shown in the second subfigure. The estimated heart-rates in beats per minute are shown in the third subfigure and the fourth subfigure shows the signal-quality indicator. Note that the signal-quality indicator distinguishes correctly the intervals of which the signal quality is beyond usefulness; the heart-rate estimator, except in those intervals with degraded signal quality, obtains correct heart-rate. This experiment, therefore, shows the viability of the proposed estimator.

In the third experiment, we show the estimator output for ECG signals measured with the person wearing sensors in *loose* contact on the skin. The original ECG data, the output of the adaptive subspace filter, the heart-rate estimate, and the signal quality indicator are shown in Fig. 7. The posture of the wearing person also changes from sitting still through walking steadily to jogging. The estimator obtains correct estimate in the period of sitting still and generates erroneous results afterwords because the ECG signal quality degrades dramatically due to the loose contact of the sensors on the skin and the motion of sensor electrodes caused by the walking or jogging of the wearing person. The signal quality indicator distinguishes correctly most time. This experiment demonstrates that while the wearable sensors may obtain ECG data with extremely poor quality, the proposed estimator combined with the signal quality indicator can extract useful information in most time.

IV. CONCLUSIONS

We have developed a real-time maximum likelihood heart-rate estimator focusing on using the wearable dry ECG sensor electrodes. We derive a simple but useful adaptive subspace filter for wandering baseline removal. We also use the FFT technique for computing the correlation value. One signal quality indicator is also proposed to indicate the degree of signal periodicity. Experiments are performed to demonstrate the viability of the proposed estimator. Since the wearable dry ECG sensor electrodes are highly susceptible to the contact motions caused by the movement of wearing person, the proposed estimator, albeit imperfect, points out the possibility to exploit the wearable technology for improving

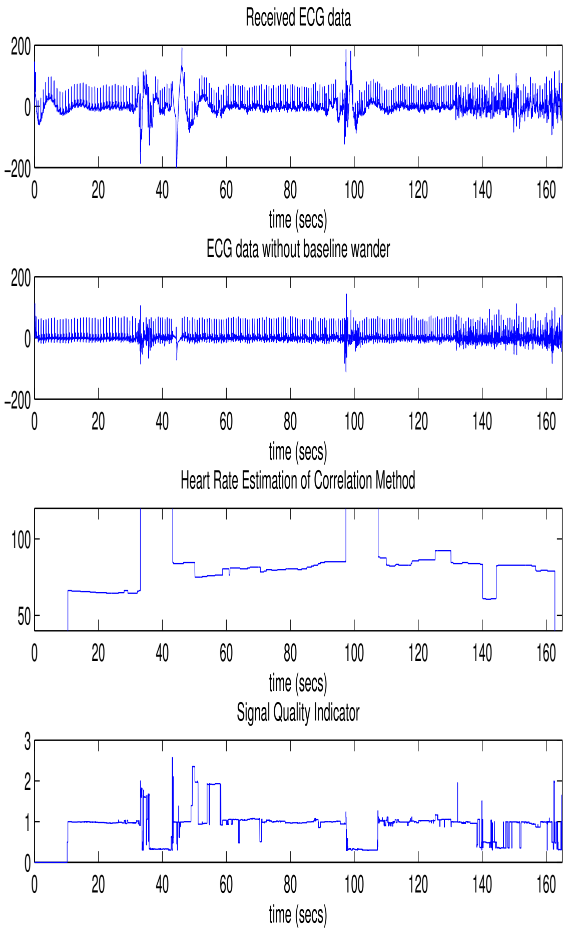

Fig. 6. The original ECG data, the output of adaptive subspace filter, the estimated heart-rate in beats per minute, and the signal quality indicator for wearing person from sitting still through walking to jogging with sensors in tight contact on the skin.

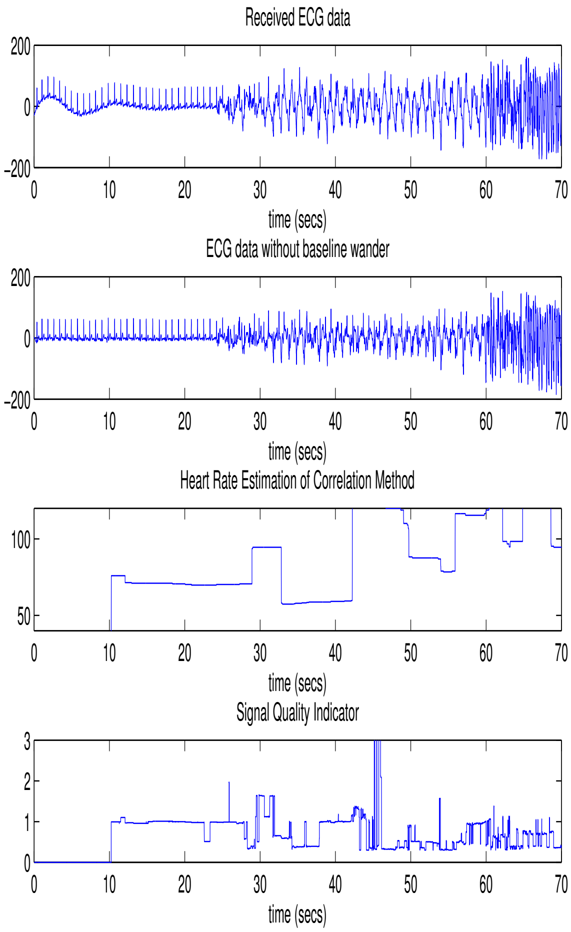

Fig. 7. The original ECG data, the output of adaptive subspace filter, the estimated heart-rate in beats per minute, and the signal quality indicator for wearing person with sensors in loose contact on the skin.

the quality of healthcare.

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