Spectral photoplethysmographic imaging sensor fusion for enhanced heart rate detection

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ABSTRACT

Continuous heart rate monitoring can provide important context for quantitative clinical assessment in scenarios such as long-term health monitoring and disability prevention. Photoplethysmographic imaging (PPGI) systems are particularly useful for such monitoring scenarios as contact-based devices pose problems related to comfort and mobility. Each pixel can be regarded as a virtual PPG sensor, thus enabling simultaneous measurements of multiple skin sites. Existing PPGI systems analyze temporal PPGI sensor fluctuations related to hemodynamic pulsations across a region of interest to extract the blood pulse signal. However, due to spatially varying optical properties of the skin, the blood pulse signal may not be consistent across all PPGI sensors, leading to inaccurate heart rate monitoring. To increase the hemodynamic signal-to-noise ratio (SNR), we propose a novel spectral PPGI sensor fusion method for enhanced estimation of the true blood pulse signal. Motivated by the observation that PPGI sensors with high hemodynamic SNR exhibit a spectral energy peak at the heart rate frequency, an entropy-based fusion model was formulated to combine PPGI sensors based on the sensors' spectral energy distribution. The optical PPGI device comprised a near infrared (NIR) sensitive camera and an 850 nm LED. Spatially uniform irradiance was achieved by placing optical elements along the LED beam, providing consistent illumination across the skin area. Dual-mode temporally coded illumination was used to negate the temporal effect of ambient illumination. Experimental results show that the spectrally weighted PPGI method can accurately and consistently extract heart rate information where traditional region-based averaging fails.

Keywords: Photoplethysmography, photoplethysmographic imaging, non-contact, heart rate

1. INTRODUCTION

Photoplethysmographic imaging (PPGI) has been gaining interest as a non-contact alternative to physiological monitoring. Existing PPGI studies have focused on extracting physiological characteristics such as heart rate,[1] respiratory rate,[2] and spatial perfusion patterns.[3] Many PPGI studies use region averaging to reduce noise and extract a blood pulse waveform (BPW). However, this approach is sub-optimal, since certain locations exhibit stronger arterial pulsations than others. For example, skin locations over a major artery may exhibit strong pulsing due, while background pixels or pixels occluded by hair will be void of blood-related pulsing. In this study, a spectral fusion approach is proposed to generate a BPW from a series of frames such that areas with higher probability of exhibiting a pulsatile signal are weighted more heavily than those that do not exhibit clean pulsing.

2. METHODS

In order to extract an estimate of a blood pulse waveform (BPW) signal from a set of frames, a pixel fusion approach is proposed. Rather than treating each pixel's temporal signal equally in an averaging scheme, each pixel is assigned an importance weight, and the pixels are aggregated using a weighted fusion scheme. The importance should rely on a metric such as signal to noise ratio (SNR); however SNR requires knowing the true signal. Thus, based on the observation that signals with high SNR exhibit low spectral entropy due to the periodic and sinusoidal-like nature of the BPW, spectral entropy was used to inversely estimate SNR.

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The frames were analyzed using a block-wise averaging approach, where the image was split into 10×10 distinct blocks, and the pixels in each block were averaged for each frame, yielding a temporal intensity signal for block i, denoted $x_k^{(i)}$. These signals were detrended in order to remove low-frequency variations due to gradual changes in lighting conditions, such as a cloud occluding the sun. A regularized least-squares detrending method was used with a smoothness criterion, represented by the second temporal derivative.[4]

Spectral entropy H for block i was calculated as:

$$H^{(i)} = -\sum_{k=0}^{N-1} p_k^{(i)} \log(p_k^{(i)}) \tag{1}$$

where N is the number of discrete frequencies, and $p^{(i)}$ is the normalized spectral power for the temporal intensity signal of block i:

$$p_k^{(i)} = \frac{S_k^{(i)}}{\sum_{j=0}^{N-1} S_j^{(i)}}, \tag{2}$$

$$S_k^{(i)} = \frac{1}{N} F_k^{(i)} \overline{F_k^{(i)}} \tag{3}$$

where $\overline{\cdot}$ is the complex conjugate, and $F_k^{(i)}$ is the kth complex Fourier coefficient using the Fourier transform:

$$F_k^{(i)} = \sum_{n=0}^{N-1} x_n^{(i)} e^{-2\pi jkn/N} \tag{4}$$

Normalized entropy was then computed as:

$$H_{norm}^{(i)} = \frac{H^{(i)}}{H_{max}} = \frac{H^{(i)}}{\log N} \tag{5}$$

Signals whose maximum frequency peak was greater than 200 bpm were deemed physiologically invalid and assigned the maximum normalized entropy value of 1.

Based on the observation that entropy is inversely proportional to SNR, an inverse exponential model was used to penalize high entropy values in a non-linearly increasing manner:

$$w^{(i)} = \exp\left(-\frac{H_{norm}^{(i)}}{\alpha}\right) \tag{6}$$

where α is a tuning parameter. The final blood pulse waveform estimate was computed using a weighted average formulation across each signal:

$$\widehat{BPW} = \frac{\sum_{i=1}^{n_i} w^{(i)} x^{(i)}}{\sum_{i=1}^{n_i} w^{(i)}} \tag{7}$$

3. EXPERIMENTAL RESULTS

For this case study, a novel Coded Hemodynamic Imaging (CHI) system was developed and used for PPGI data acquisition.[5,6] Designed for high-quality, robust PPGI acquisitions at a distance, the CHI system consisted of a near infrared (NIR) sensitive camera (GS3-U3-41C6NIR-C, Point Grey) with an 850–1000 nm optical bandpass filter fitted in front of the lens, and a spatio-temporally coded light source used for active illumination. The spatio-temporal coded light source of the CHI system consisted of an 850 nm high powered LED, driven by both a 20:1 temporal code for ambient correction,[5] and a grid spatial code for increased penetration depth. The bottom half of the face and neck were illuminated. Upon collecting the reflectance data, the data were processed using the proposed fusion technique in MATLAB, yielding an estimation of the true signal, $\widehat{BPW}$.
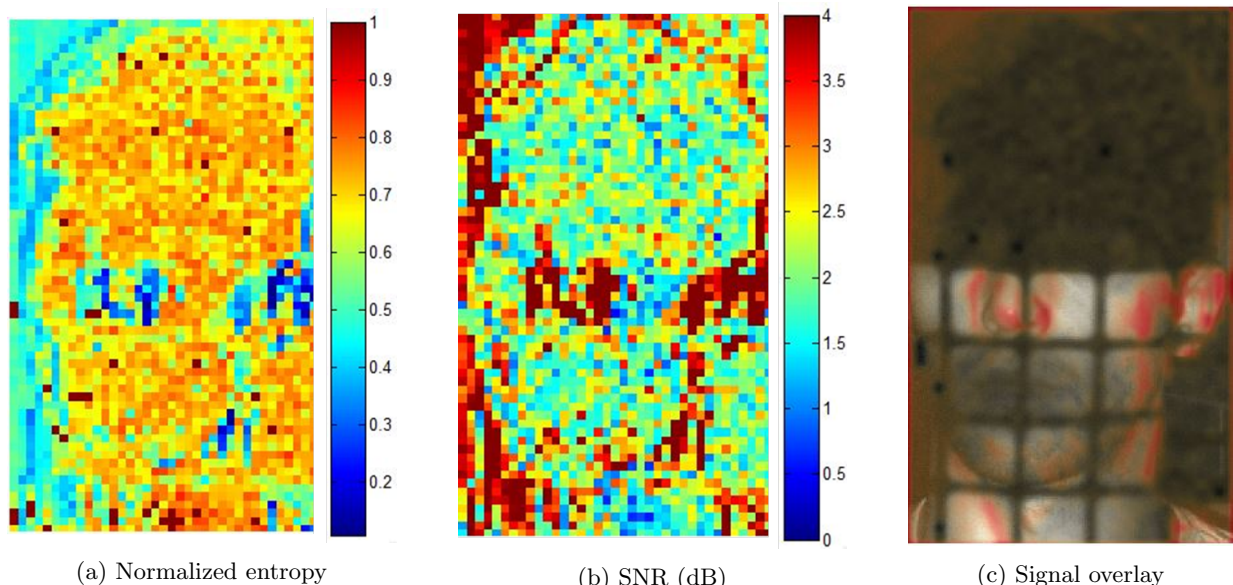
(a) Normalized entropy   (b) SNR (dB)   (c) Signal overlay

Figure 1: Entropy and SNR maps. Areas of low entropy (a) (blue) correlate with areas of high SNR (b) (red). Overlaying the pulsatile areas onto the original image (c) show thats pulsatile components around the nose, outside cheek, ears, and outer neck.

Figure 1 shows the spatial entropy and SNR maps. Areas that exhibit low entropy (blue) are correlated with areas of high SNR (red). Figure 1c shows pulsatile points around the nose, outside cheek, ears, and outer neck. These are the areas that the fusion reconstruction weighs heavily.

Figure 2 shows the result of fusion reconstruction compared to the mean reconstruction across the region of interest. In the top panel, the fusion method produces distinct peaks from the imaging data (blue) that are consistent with the true BPW (red), compared to the waveform in the mean construction which does not exhibit pulses with systolic peaks. This is further emphasized in the frequency domain, where the fusion reconstruction yields a power spectral density plot with very similar shape to that of the true BPW, yielding a clean frequency peak at the heart rate frequency. In contrast, the heart rate is not discernible in the mean reconstruction, and the power spectral density is not consistent with the true BPW plot.

4. CONCLUSIONS

In this study, a spectral fusion method was proposed to provide an accurate estimation of the true blood pulse waveform. In this method, pixels were assigned weights according to their spectral energy distribution. Experimental results demonstrated that the fusion reconstructed blood pulse waveform exhibited a cleaner temporal signal and accurate spectral power distribution with an easily discernible heart rate frequency peak compared to the mean reconstruction.

ACKNOWLEDGMENTS

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(a) Fusion reconstruction, temporal

(b) Mean reconstruction, temporal

(c) Fusion reconstruction, frequency
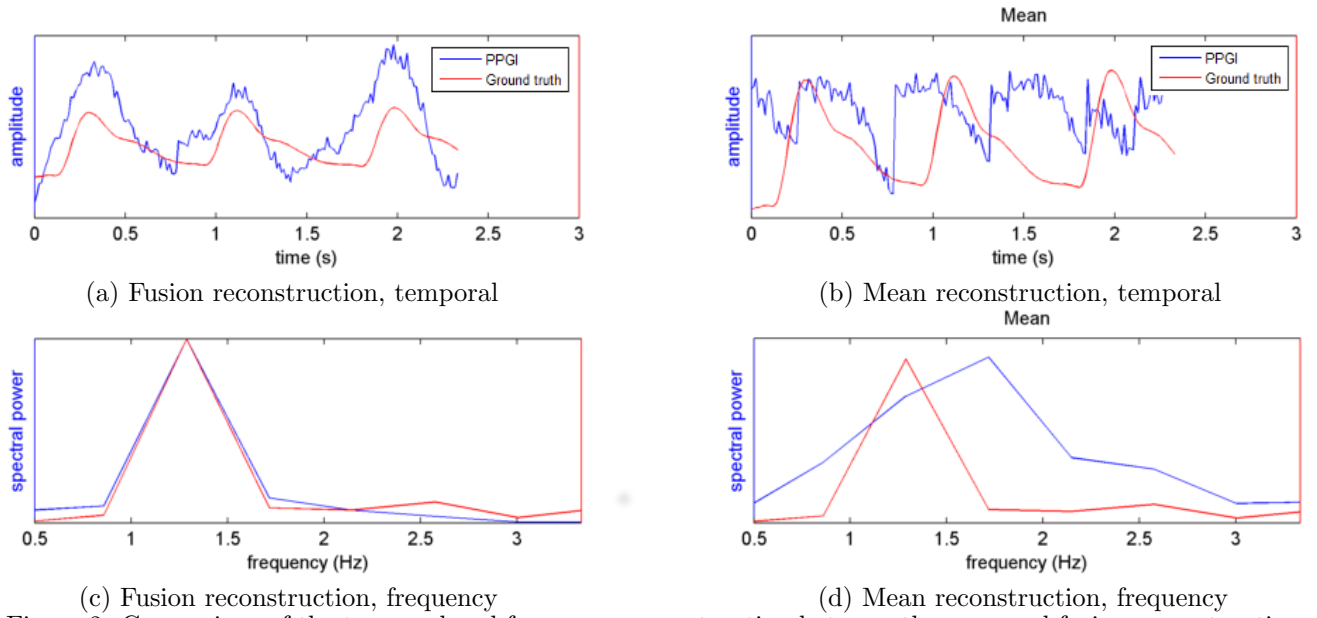

(d) Mean reconstruction, frequency

Figure 2: Comparison of the temporal and frequency reconstruction between the proposed fusion reconstruction and the typical mean region of interest approach. The temporal fusion reconstruction (a) (blue) exhibits pulsing characteristics consistent with the true blood pulse waveform (red), whereas the mean reconstruction (b) (blue) does not exhibit clean pulsing with systolic peaks. The heart rate frequency is clearly discernible in the fusion reconstruction (c), but not the mean reconstruction (d).

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