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Pulse Wave Sensor for Non-intrusive Driver's Drowsiness Detection

Shan Hu, Ryan L. Bowlds, Ye Gu, and Xun Yu

Abstract—**This research proposes a PVDF film pulse wave sensor for use in driver's drowsiness detection. The sensor non-intrusively measures heart pulse wave from driver's palm and an adaptive filter is employed to cancel the measurement noise aroused by the changing of gripping force. Experimental results show clear pulse wave signals can be obtained. Two-hour driving simulation is performed for drowsiness detection tests. The low frequency to high frequency (LF/HF ratio) is calculated from power spectrum density (PSD) of subjects' heart rate time series. The LF/HF ratio shows decreasing trends as subjects go from awake to drowsy.**

I. INTRODUCTION

DRIVER drowsiness is one of the major causes of serious traffic accidents. According to the National Highway Traffic Safety Administration (NHTSA) [1], there are about 56,000 crashes caused by drowsy drivers every year in US, which results in about 1,550 fatalities and 40,000 nonfatal injuries annually. A technique that can real-time detect the drivers' drowsiness is of utmost importance to prevent drowsiness-caused accidents. If drowsiness status can be accurately detected, incidents can be prevented by countermeasures, such as the arousing of driver and deactivation of cruse control.

A. Review of Drowsiness Detection Techniques

A number of efforts have been reported in the literature on the developing of drowsiness detection systems for drivers. These drowsiness detection methods can be categorized into two major approaches.

1) Imaging processing techniques [2,3]: this approach analyzes the images captured by cameras to detect physical movements of drivers. For example, the PERCLOS system developed by W. W. Wierwile *et. al.* used camera and imaging processing techniques to measure the percentage of eyelid closure over the pupil over time [2]. Although this vision based method is non-intrusive and will not cause annoyance to drivers, the drowsiness detection is not accurate, which is severely affected by the environmental backgrounds, driving conditions, and driver activities (such as turning around, talking, and picking up beverage). In addition, this approach requires the camera to focus on a relative small area (e.g. around the driver's eyes). It thus requires precise camera focus adjustment for each driver.

2) Physiological signal detection techniques [4, 5]: this approach is to measure the physiological changes of drivers from biosignals, such as the electroencephalogram (EEG), electrooculograph (EOG), and electrocardiogram (ECG or EKG). Since the sleep rhythm is strongly correlated with brain and heart activities, these physiological biosignals can give accurate drowsiness detection. However, all the researches up to date need electrode contacts on drivers' head, face, or chest. Wiring is another problem for this approach. The electrode contacts and wires will annoy the drivers, and are difficult to be implemented on vehicles.

This research uses the heart rate signals to detect drowsiness and aims to overcome the limitation of current methods by developing non-intrusive, easily implementable and accurate heart rate sensors.

The spectral analysis of time series of heart rate can be used to calculate the heart rate variability (HRV) – the variations of beat-to-beat intervals in the heart rate [6]. HRV has three main frequency bands: high frequency band (HF) that lies in 0.15 – 0.4 Hz, low frequency band (LF) in 0.04 – 0.15 Hz, and very low frequency (VLF) in 0.0033 – 0.04 Hz [6]. A number of psychophysiological researches found that the LF to HF power ratio (LF/HF ratio) decreases when a person changes from the awake into drowsiness (or early stage of sleep) [7, 8]. The HRV analysis therefore can be an effective method to detect driver drowsiness.

B. Review of Heart Rate Signal Measurement

The key to the proposed drowsiness detection approach is to have an accurate and non-invasive heart rate signal measurement system.

Heart rate can be derived from peak-to-peak interval time series of the electrocardiogram (ECG). Several research groups have tried to develop non-intrusive ECG measurement using active electrodes [9, 10]. During our reproducing experimental test, we found that satisfactory ECG signal can be obtained if the people sit still on the chair and no external vibration involved; both conditions are rarely occurred for vehicle applications. Another fundamental problem with this active electrodes based non-contact ECG measurement is that the measurement is extremely sensitive to impedance changes and disturbance, which might be attenuated by tightly attach the electrodes to human body. However, it becomes an intrusive measurement. In our previous research [11], flexible

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electrically conductive fabric on the steering wheel is used as ECG electrodes and clear ECG signal can be obtained (shown in Figure 1). This configuration is non-intrusive to the driver. However, this approach requires driver's both hands on the steering wheel; no ECG signal can be obtained when the driver put single hand on the steer.

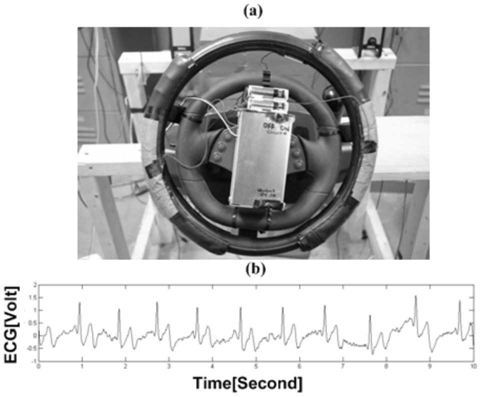

Fig. 1. (a) ECG measurement system on steering wheel. (b) is the ECG measurement results.

Recently, the piezoelectric films have been utilized to detect pulse wave [12, 13]. Piezoelectric films detect the dynamic pulse forces arose from the blood flow. Because of its high piezoelectric response, piezo-polymer PVDF (polyvinylidene fluoride) films have been investigated for pulse wave measurements. Lin *et al.* tried to measure pulse wave from driver's palm using PVDF films [12]. This is a non-intrusive approach and very promising results were reported for still human positions. However, the pulse wave measurement is severely affected by noise caused by the change of gripping force. The gripping force noise can not be effectively eliminated by typical filtering circuits, because its frequency overlaps with the frequency of pulse wave. Therefore, a technique to cancel this noise poses a major challenge for the pulse wave measurement by PVDF sensor and the following HRV analysis for driver drowsiness detection. This challenge will be addressed by adaptive noise cancellation techniques proposed in this research.

II. METHODS

A. Configuration of Pulse Wave Sensor

The configuration of the proposed pulse wave sensor is illustrated in Figure 2. An array of pulse wave sensor will be installed around the inner circle of the steering wheel to measure heart pulse wave, which can ensure the detection even with single hand driving only. Each sensor unit has a pair of two PVDF films and isolation foam inserted between the two films. The PVDF film on top that contacts with the driver's palm (Film-1) is used to measure the heart pulse wave; the one on the bottom that contacts with the steering wheel (Film-2) is used to measure the gripping force noise. The foam is inserted to isolate heart pulse from the bottom film so that the film can provide a "pure" gripping force noise reference for the adaptive filter.

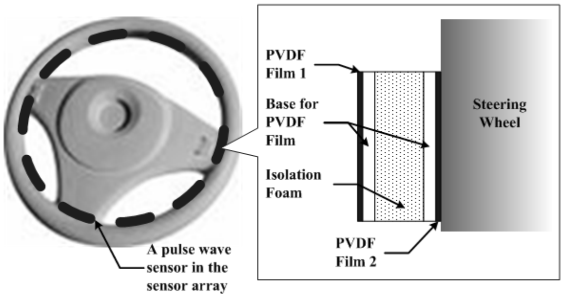

Fig. 2. Configuration of proposed pulse wave sensor.

B. Noise Cancellation by Adaptive Filter

A feedforward adaptive noise cancellation approach is proposed to eliminate the effects of changing gripping force on the heart pulse wave measurement. Figure 3 illustrates the block diagram of the feedforward adaptive filter. The primary input of the filter is the measurement from the PVDF Film-1, which is the mix of desired pulse wave signal $s(n)$ and gripping force noises n_1. $u(n)$ is the measurement from PVDF Film-2, which will be "pure" gripping force due to the isolation by the foam. $u(n)$ is used as the feedforward noise reference signal for the adaptive filter. $e(n)$ is the error signal. $y(n)$ is the output of the adaptive filter. Since the desired pulse wave signal is uncorrelated with the gripping force noises, $e(n)$ will be the best estimation of the pulse wave signal $s(n)$ if $u(n)$ is a good noise reference and $y(n)$ is close to $u(n)$. The adaptive filter will minimize the error signal $e(n)$ via minimizing the instantaneous squared error, $\hat{\xi}(n) = e^2(n)$. Least-mean-square (LMS) algorithm will be used to adapt the adaptive filter coefficient $w(n)$ [14], which updates the coefficients of $w(n)$ in the negative gradient direction with appropriate step size μ. Here, the adaptive filter uses a step size of 0.01 and an order of 16.

$$\bar{w}(n+1) = \bar{w}(n) - \frac{\mu}{2}\nabla\hat{\xi}(n) \tag{1}$$

where $\nabla\hat{\xi}(n)$ is the instantaneous estimate of the mean square error gradient at time n, and can be expressed as

$$\nabla\hat{\xi}(n) = 2[\nabla e(n)]e(n) = -2u(n)e(n) \tag{2}$$

By substituting (2) back into (1), we obtained the least mean square adaptation law

$$\bar{w}(n+1) = \bar{w}(n) + \mu u(n)e(n) \tag{3}$$

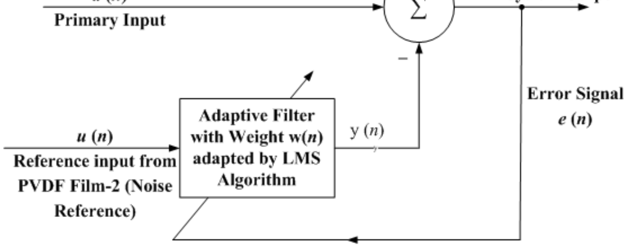

Fig. 3. Block diagram of the feedforward adaptive filter.

C. *Driving Simulation*

A driving simulator is used to test the drowsiness detection system. The simulator has a screen to display the virtual reality driving environment, a real-size driver seat and a steering wheel with pulse wave sensors. A subject was asked to drive with the simulator non-stop for two hours. The subject's heart rate was continuously recorded by the heart pulse sensors installed on the steering wheel. A camera was used to capture the video of driver's behavior. The video will serve as a reference for driver's drowsiness level.

D. *HRV Analysis for Drowsiness Detection*

As heart pulse signal is recorded during driving simulation, HRV analysis will be performed to extract information for drowsiness detection. First, a heart pulse peak detector computes the peak-to-peak interval (or heart rate) time series. Since the time intervals between heart pulses are not uniform, resampling is needed to turn the original heart rate time series into evenly sampled. Then the resampled time series is analyzed in two domains: frequency domain and time-frequency domain. In frequency domain, the power spectral density (PSD) of every five minutes' heat rate time series will be estimated by the autoregressive method [15]. Autoregressive method is by far the most widely used method in research on HRV and sleep stages [7, 8]. In order to compare our result with that of available literature, autoregressive method is chosen instead of Fast Fourier Transform. Five minute duration is chosen according to standard of HRV analysis. [6] Then the PSD is divided into three main frequency bands: high frequency band (HF) that lies in 0.15-0.4 Hz, low frequency band (LF) in 0.04-0.15 Hz, and very low frequency (VLF) in 0.0033-0.04 Hz. A number of psychophysiological researches found that the LF to HF ratio (LF/HF ratio) decreases when a person becomes sleepy [7, 8]. As a result, we choose to calculate LF/HF ratio instead of other kinds of HRV.

For time-frequency analysis short-time Fourier transform (STFT) is performed on heart rate time series to see how the heart rate frequency contents change as the driver becomes drowsy. The STFT uses a window to slide through heart rate time series and perform Fourier transform inside each window. The result of STFT is a spectrogram showing the magnitude of the STFT versus time. The STFT used Hamming window with length of 1024, and windows are overlapped by 900 samples.

III. RESULTS

A. *Heart Pulse Wave Measurement and Adaptive Filter Noise Cancellation*

Fig. 4 shows the heart pulse wave measurement and the results with adaptive noise filter. Fig. 4(a) shows the original measured signal from PVDF Film-1, which is clear for most still positions but is heavily polluted when there is gripping force changes (the gripping force is show in Fig. 4(c) as measured by PVDF Film-2). Fig. 4(b) shows the heart rate pulse signal after the adaptive noise filter. The result demonstrates that the configuration of pulse wave sensor is effective in measuring pulse wave sensor and the inner PVDF Film-2 can provide effective measurement of gripping force to provide the noise reference for the adaptive filter. More importantly, the adaptive filter can successfully remove spurious pulse waves caused by changing of gripping force, as well as pick out pulse waves from noisy background.

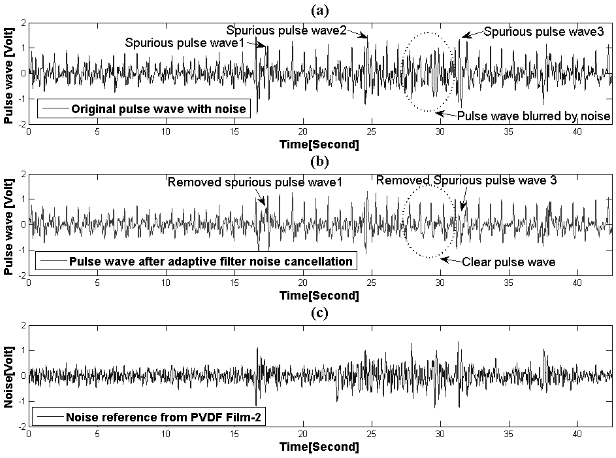

Fig. 4. Noise cancellation result from adaptive filter. (a) is the pulse wave with noise from PVDF Film-1: there are three spurious pulse waves caused by the change of gripping force, and there is a section of signal that is so blurred by noise that the heart pulses can not be recognized. (b) is the pulse wave after adaptive filter noise cancellation: two out of three spurious pulse waves are removed, the one is not removed possibly because it is not introduced by changing of gripping force. The blurred heart pulses are also successfully picked out from noise. (c) is the noise reference for adaptive filter from PVDF Film-2.

B. *Results of HRV Analysis during Driving Simulation*

Two health subjects (male, 24 and female, 24) were recruited for two-hour driving simulation. At the beginning, the subjects were not sleepy at all: the eye movements were quick and the body movement was active; whereas at the end, the drivers seemed very sleepy: eye blinking occurred slowly, the eyelids were shut sometimes and yawning happened frequently with deep respiration. The LF/HF ratios for both subjects during driving simulation are shown Figure 5. As

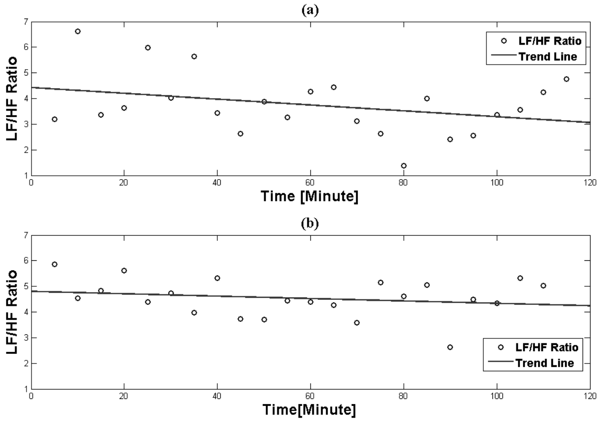

Fig. 5. LF/HF ratio during two-hour driving simulation. (a) and (b) are the LF/HF ratios and trend lines for female and male subject respectively.

getting drowsy, both subjects' LF/HF ratios show a decreasing trend. However, the slope of the trend varies among two subjects. The spectrograms of two-hour heart rate time series for both subjects are shown in Figure 6. The HF and LF ranges are marked out. The bright color on spectrogram stands for high power in frequency domain. As the subjects became drowsy, both spectrograms showed the increase of bright color (or increase of power) in HF range. This could be part of the reason why the LF/HF ratio has a decreasing trend. The results of HRV analysis during two-hour driving simulation are in accordance with previous psychophysiological researches on the relationship between sleep stages and HRV. The results prove that the proposed heart pulse wave sensor and adaptive filter are effective in measuring reliable heart pulse for HRV analysis.

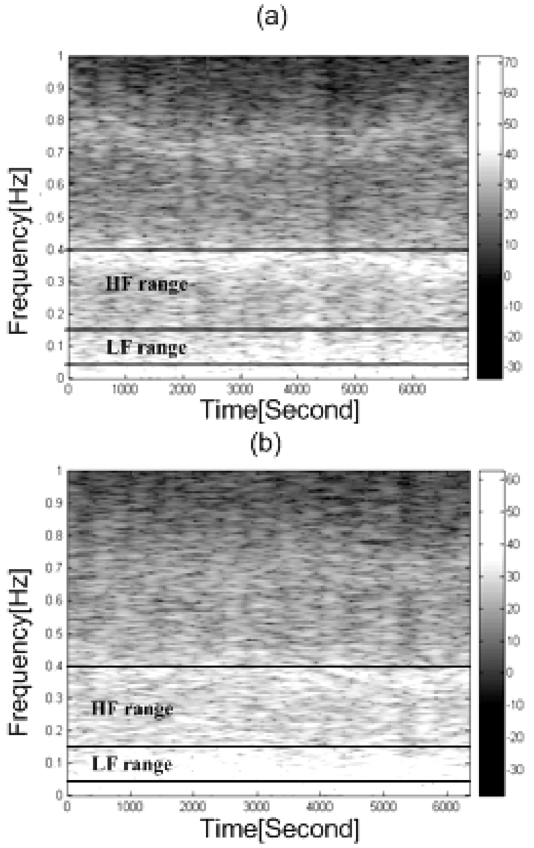

Fig. 6. Spectrogram of two-hour heart rate time series (a) and (b) are spectrogram of female and male subjects respectively

IV. CONCLUSION

In this research, PVDF pulse wave sensor had been developed to measure heart pulse from driver's palms for drowsiness detection. The sensor is non-intrusive and can be easily installed on vehicle steering wheel. An adaptive filter algorithm was designed to eliminate the measurement noise caused by the changing of gripping force. Experimental results showed that sensor with the adaptive filter can provide clear heart pulse wave for later heart rate variability analysis. Two hour driving simulation was conducted on two subjects. The proposed sensor was successful in continuously monitoring the heart rate of subjects for during simulation. HRV analysis on the two hour heart rate time series showed that LF/HF ratio had a decreasing trend as both subjects became drowsy, although the slope of trend were different between subjects. According to the time-frequency analysis of heart rate time series, the decreasing trend can partially due to the increase of power in HF range.

Since each individual has unique HRV pattern (e.g. the different decreasing trend slopes observed from two subjects), future research to create personalized drowsiness detection criterion is needed.

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