35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Wireless-based Portable EEG-EOG Monitoring for Real Time Drowsiness Detection

J. Arnin, D. Anopas, M. Horapong, P. Triponyuwasi, T. Yamsa-ard, S. Iampetch and Y. Wongsawat, *Member, IEEE*

***Abstract*— Drowsiness is one of the major risk factors causing accidents that result in a large number of damage. Drivers and industrial workers probably have a large effect on several mishaps occurring from drowsiness. Therefore, advanced technology to reduce these accidental rates is a very challenging problem. Nowadays, there have been many drowsiness detectors using electroencephalogram (EEG), however, the cost is still high and the use of this is uncomfortable in long-term monitoring because most of them require wiring and conventional wet electrodes. The purpose of this paper is to develop a portable wireless device that can automatically detect the drowsiness in real time by using the EEG and electrooculogram (EOG). The silver (Ag) conducting fabric consolidated in a headband used as dry electrodes can acquire signal from the user's forehead. The signal was sent via the wireless communication of XBee® 802.15.4 to a standalone microcontroller to analyze drowsiness using the proposed algorithm. The alarm will ring when the drowsiness occurs. Besides, the automatic drowsiness detection and alarm device yields the real-time detection accuracy of approximately 81%.**

I. Introduction

Drowsiness refers to feeling sleepy during the day which can reduce ability to function and slow down response time. This may lead to fall asleep in inappropriate situations or places. The dangers of drowsiness can occur when people perform tasks that require concentration such as driving, and machinery working. Drowsy driving is one of the top causes of car accidents [1]. Drowsiness is the factor leading to road accidents since it can impair performance, slower reaction time, and reduce vigilance and attention of the driver [2]. Due to severe damage, driver drowsiness detection and warning is the useful solution which can prevent the risk of collisions.

Drowsiness can be detected by several methods. They can be divided into 2 major kinds of systems [3]. "Vehicle oriented" [4] is the methods that analyze indirect information i.e. affected from drowsy behavior, such as steering angle, vehicle speed, or turn indicator, to indicate drowsiness of the driver. However, these driving behaviors may be different in each driver. Therefore, the disadvantage of this method is the difficulty of specifying the normal driving model and drowsy driving which can be used to detect variation in each driver's behavior. The second method is "driver oriented" [5]. This method uses physiological measurement such as eye or face movement, blink rate, or yawning. Furthermore, vital signs, like electroencephalography (EEG), electromyogram (EMG), or heart rate, are also used to indicate drowsiness. This approach is more reliable than the previous method since the physiological information depend directly with drowsiness.

Research supported by NRU Funding of Mahidol University.
J. Arnin*, D. Anopas, M. Horapong, P. Triponyuwasi, T. Yamsa-ard, S. Iampetch and Y. Wongsawat** are with the Department of Biomedical Engineering, Mahidol University 25/25 Putttamonthon 4, Salaya, Nakornpathom 73170, Thailand (corresponding author, phone: 66-82-889-2138 Ext 6361; fax: 66-82-889-2138 Ext 6366; e-mail: *jetsada.arn@ student.mahidol.ac.th, **yodchanan.won@mahidol.ac.th).

The driver assistive systems available in the market nowadays have been reviewed in this paragraph. In Bosch's driver drowsiness detection system [6], the level of drowsiness is determined by information from the steering-angle sensor. Ford's driver alert [7] has front and side cameras for lane detection and tracking. Fatigue detection system video camera in Volkswagen [8] monitors head movement and facial features. Toyota driver monitoring system [9] uses CCD cameras with infrared LED for eye movement monitoring.

For physiological measurement, EEG is the signal that can early detect drowsiness from the brain directly. Theta (4-8 Hz), alpha (8-13 Hz), and beta (13-30 Hz) frequency bands of EEG are different between normal state and drowsy state [10]. Hence, these frequency bands are used to evaluate drowsiness. In addition, electrooculogram (EOG), which measure eye blink and eye movement, is also widely used to detect drowsiness. The blink rate in drowsy person is slower as well as eye closure duration is longer [11]. These characteristics of ocular behavior are used to analyze drowsiness.

In this paper, the EEG-based and EOG-based early drowsiness detection system is proposed. This system uses wireless EEG amplifier and electrode which are developed by ourselves thus it can reduce cost of the system. As shown in Fig. 1, the overview of the system includes two main parts i.e. sender unit and receiver unit. We detect and analyze the information directly from the driver's brain and ocular muscle. Thereby, the proposed system is real-time, reliable, wireless, and low-cost. Not only be used by drivers, this system is also proper with other risk tasks such as machinery working.

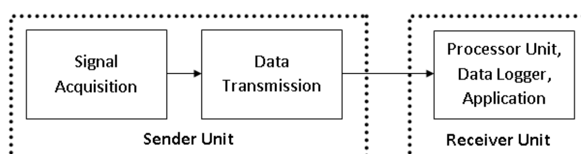

Figure 1. The overall system of drowsy detection device

II. Signal Features and Algorithms

Since the acquired signal is measured from frontal lobe (forehead), so both EEG and EOG are combined as one signal. Therefore, feature extraction algorithm needs to employ both time and frequency-domain analysis. The time-domain was used to analyze the phenomena of EOG whereas frequency-domain was performed for EEG feature. Both analyzed approaches are processed simultaniouly every 2 seconds.

A. Electrooculogram

Electrooculogram (EOG) is a technique to measure resting potentials of a retina. Normally, eye movements and eye blink can be obviously detected by electrooculograms. Characteristics of eye movements depend on directions of user gazing and the position of electrode placement. If a positive electrode is attached on the left side of user's eyes and a negative electrode is attached on the right side, the signal will increase from resting state when the eyes move from center to left side. On the other hand, if the positive electrode is attached on the right side of user's eyes and the negative electrode is attached on the left side, the signal will decrease from resting state when the eyes move from center to left side. Therefore, the visual direction of user can be detected by means of this approach.

According to [12], blinking signals may be above or below the resting potential of the retina that depends on the position of the electrode. If positive electrode places above the eye, the signal will increase from resting state when your eyes blink. If positive electrode places below the eye, the signal will decrease from resting state when your eyes blink. Blink duration is about 202.24 milliseconds in alert state. In drowsy state, blink duration is about 258.57 milliseconds. Another feature is the shape and frequency of eye blink in many states and can be used to detect the drowsy state. Fig. 2 displays the characteristic of eye blink signal.

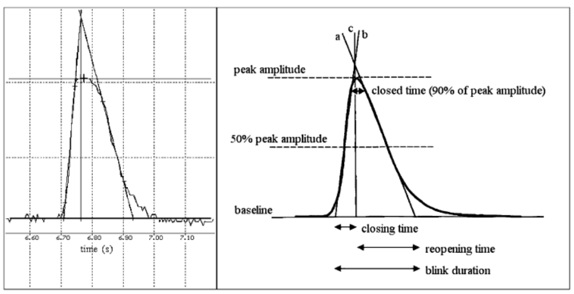

Figure 2. Characteristic of eye blink signals [12]

Besides, when a person feels drowsy, eye behavior closes longer than 1 second and eye blink decreases from normal state. In normal state, people blink about 12 to 15 times in 1 minute and mean value of blink duration is 202.24 milliseconds and closing time is 63 milliseconds. On the other hand, mean value of blink duration is 258.57 milliseconds in drowsy state and closing time is 71.06 milliseconds. Another feature of interest is the frequency of eye blinking. If eye blinks and eye movements are slower, this would tell state of drowsiness. Therefore, we employed eye blinks and eye movements to develop an algorithm for detecting the state of drowsiness.

For our experiment, three participants were tested to find the frequency of eye blinks and eye movements in drowsy state. When the participant showed the sign of drowsiness or alpha wave, the characteristic of their eye blinks and eye movements were observed and found that in 6 seconds if eye behaviors do not perform, alpha wave would occur. Thereby, this characteristic was used in our algorithm and was a condition of alarm. To detect eye blinks and eye movements, energy of EOG signal was employed. Since the characteristics of eye blinks and eye movements depend on the user, so our systems have an automatic calibration for each user. The auto-calibration will firstly record the signal 2 minutes and also automatically calculate baseline for EOG. After recording, the maximun of signal (peak) will be found at three peaks to initiate the threshold. The thredhold of eye blink is 80% of the average maximum. Also while running program the baseline will be newly calculated every 3 epochs (6 seconds) to adjust a new threshold within limited boundaries. After that the system also calculated the energy of eye behavior in each subject to detect eye blinks and eye movements. If the signal is in the range of eye behavior, eye blinks and eye movements will perform. If the signal exceeds a range of eye behavior, artifacts will perform. Thereby, our systems can detect eye behavior out of artifacts and use eye behavior to detect state of drowsiness.

B. Electroencephalogram

EEG is an electrical signal of the brain acquiring via electrodes attached on the scalp with conductive gel [13], [14]. EEG signals can normally classify based on frequency ranges. The frequency ranges can be detected in a different state. Ranges of frequency include delta wave (2-4Hz), theta wave (4-7Hz), alpha wave (7-13Hz), beta wave (13-30Hz) and gamma wave (30-100Hz). Some characteristics of frequency range can represent the state of person such as an alpha wave appears in the posterior regions of the head on both sides. It occurs when the subject is in the resting state, or eye closing. Furthermore, beta wave occurs when the subject is active, busy or anxious thinking and active concentration. This wave can be measured from the frontal and parietal regions. Therefore, the state of drowsiness can be measured from the characteristic of those frequencies.

In drowsy state, alpha band, beta band and theta band occur differently from normal state. According to [11], the weighted-frequency index was used to indicate state of drowsiness. Alpha band occurs when a person performs a relaxed awareness. Thereby, alpha band is the sign of drowsiness state. Beta band occurs when a person is highly alert and well focus. Therefore, this range decreases when drowsiness state performs. Theta band was also reported to indicate the drowsiness [11] as well as the first stage of sleep and daydreaming. Hence, we utilized those mentioned frequency bands in [11] to detect drowsiness. The condition is

$$I(t) = \frac{0.6\theta(t) + 0.4\alpha(t)}{0.5\beta(t)} \quad (1)$$

where 0.6, 0.4, and 0.5 are the individual weight of theta, alpha, and beta bands, respectively. The $\theta(t)$, $\alpha(t)$, and $\beta(t)$ were calculated from the power spectrum of theta band, alpha band, and beta band, respectively. This index are used to classify the drowsiness state by means of EEG real-time detection. As in (1), the accuracy of this weighted-frequency is 90.39%. Threshold of drowsy state can be found by asking the users to close their eyes and employ half amount of the amplitude of $I(t)$. The condition to alarm is that if $I(t)$ is greater than the threshold longer than 6 seconds the system will alarm.

III. SIGNAL ACQUISITION AND PROCESSING

Signal acquisition and processing is an important step to measure drowsiness phenomenon. According to Fig. 1, our design have 2 main units including sender unit and receiver unit. The sender unit consists of electrodes, signal acquisition and data transmission. The receiver unit is composed of processor unit, data logger, and alarm application.

A. Electrodes

There are many types of electrode used to acquire biosignals e.g. cup electrode, surface electrode, dry electrode, and electrode cap. The most convenient type is dry electrode that does not need any conductive gel. As shown in Fig. 3, pad was designed in a suitable size for a forehead attached with three dry electrodes. By using the conducting fabric (92% silver-plated and 8% nylon) as the sensor, we can easily attach it to the forehead. Sponges were used for enhancing the contact area between the fabric and forehead. Snap button was coated with silver for good conductivity. Finally, dead strap was able to adjust the size to fit with every user's head.

Figure 3. Conducting pad used as three dry electrodes

B. EEG Acquisition Processes

In this paper, we have developed our home-made EEG amplifier circuit which consists of 1) voltage follower 2) instrument amplifier 3) DC restoration 4) drive right leg 5) bandpass filter. For the filter part, we set a passband cutoff frequency from 0.5-30 Hz. The gain of this amplifier was approximately 65,000 calculated by multiplying gain from the instrument amplifier state and the bandpass filter state.

Another part that must be considered is the power supply and charging circuit. A lithium polymer battery, 3.7V 700mAh, was used as power supply for all circuits. It can be used for more than 10 hours. A power from the battery was regulated to 3.3V by using a low - dropout regulator, MIC5200. The recharging circuit employed the MCP7383 by setting current 200 mA to recharge a battery. Micro USB was used to charging port. Fig. 4 illustrates the wireless sender unit that is a two-layer 3.6 cm × 4.1 cm printed circuit board.

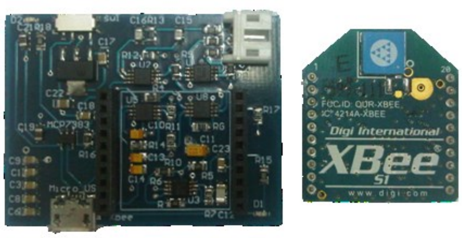

Figure 4. The wireless sender unit

C. Data Transformation and Transmission

An analog signal from a circuit was transformed to digital signal and transmited by XBee® 802.15.4. The internal ADC of XBee® 802.15.4 was employed to reduce a power from microcontroller and circuit board area with 10-bit ADC resolution. For the sender unit, a digital signal transmitted to a receiver unit by XBee® 802.15.4. The system was designed to one by one matching with 333Hz sampling frequency and 16 bytes frame data. For receiver unit, another Xbee was used to receive data and send information to microcontroller by UART port.

D. Signal Processing and Application

After the receiver unit obtains data from the sender unit, the signal was processed by means of our proposed algorithm to monitor drowsiness levels, i.e. either EEG or EOG (measuring with the same electrode as EEG at forehead) regarding the drowsy state was detected. A receiver unit consists of regulator, processor unit, Xbee module, data logger (Micro SD card), and alarm device. The 12V DC buzzer was used as alarm sound. To alarm the user, we designed an alarm application for 2 levels that there are normal and severe controlled by the microcontroller. Power supply for receiver board is from 12V cigarette lighter on a car console. The power supply was used to operate two distinct voltages. One was regulated by LM2575 for setting a voltage to 3.3V for supplying processor unit, Xbee module and its supplements. Another is to supply buzzer for alarm sound directly. A digital signal was processed by STM32F4discovery module from STMicroelectronics. This module used Arm Cortex-M4 32 bit STM32F407VGT6 as the main microprocessor. Besides an alarm application, the system also records raw data of the signal with respect to time and writes a data logger to micro SD card for further statistical analysis.

For the processing steps, both EOG and EEG will be firstly employed for calibrating the threshold; the first 2 minutes after opening the power switch the user will be asked to be motionless for EOG calibration and next 1 minute he/she needs to close his/her eyes for EEG calibration. After doing the calibration, if the user reaches drowsy stage that meets both EEG condition and EOG condition for 6 seconds, the system will alarm by sound and light.

IV. Experiments and Results

According to the designed system, performance evaluation of the system were required to ensure the quality and reliability, thus the device was tested in the precise experiment. The experiment for testing was separated into 3 parts consisting of EEG amplifier, electrode testing, and classification results.

A. EEG Amplifier Testing

Amplifier was tested by the qualitative measurement of EEG signal. For this EEG testing, 10-20 system was used as electrode position that electrodes were placed on T3, P4 and C3 which alpha rhythm obviously occurs in temporal lobe. In the experiment, subject was asked to sit motionless during recording their EEG signal for open eyes and close eyes activities. The recorded EEG waveforms were shown in Fig. 5. The upper graph represents signal during periods of eyes closeing and the lower one indicates brainwaves while eyes openning. The fast Fourier transform (FFT) approach was used to classify the frequency of EEG signal. The result of both opened eyes and close eyes EEGs in frequency domain were shown in Fig. 6. As the result, we can observe high amplitude of alpha band while subject closed eyes comparing with opened eyes. The results are consistent with the principle of EEG that alpha wave was observed while relaxing, sleeping and closing eyes.

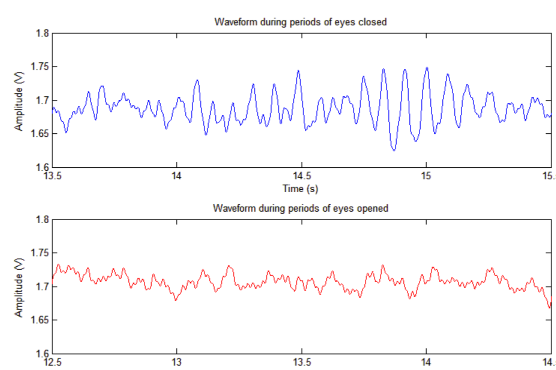

Figure 5. EEG signals received from sender unit

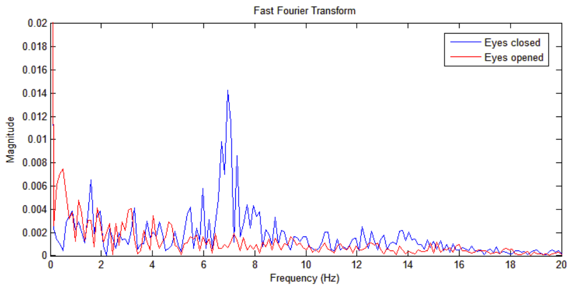

Figure 6. Power spectrum results of EEG signals

Figure 7. A portable wireless drowsy detection device

B. Electrode testing

The Electrode pads were measured the impedance by Model 1089NP Checktrode. The meaning and indicated value of impedance are classified into 4 states. The first state is 5 kΩ or less that means it is excellent for signal measurement. The second state is 5-10 kΩ that means it is good for signal measurement. The third state is 10-30 kΩ that means we should remove the electrode and prepare skin for better signal measurement. The last state is above 30 kΩ that means a little movement will cause noise. Electrodes are removed and skin is prepared for signal measurement. The impedance of electrode pads was measured and the average of impedance was 8.2 kΩ which was shown to be reliable.

C. Classification Results

The algorithm of designed system was proved with driver simulation by three subjects. The driver simulation was set up by using car racing game. Subjects used steering wheel and pedal for racing game. In this procedure, subjects were asked to drive for 2 hours and immediately press a button placing next to them when feeling drowsy to manual-identify as drowsy stage for comparing with the auto-detection algorithm of the device. The accuracy of the system was evaluated from sensitivity and specificity. The sensitivity represents the ratio of actual positives which are correct detection (The percentage of system which alarm correctly when subjects are drowsiness). The specificity represents the ratio of actual negatives which are correct detection (The percentage of system which does not alarm when subjects are active). The results are shown in Table I.

TABLE I. RESULTS OF AUTOMATIC DROWSINESS DETECTION SYSTEM

	%Sensitivity	%Specificity
Subject1	82.4	80.5
Subject2	78.3	79.8
Subject3	85.8	82.6

According to Table I, the system can classify drowsiness with acceptable accuracy. The specificity of each subject was approximately 82% with the sensitivity about 81%.

V. CONCLUSION

Development of the drowsiness detection prototype using both EEG and EOG approaches has been presented in this paper. This system uses portable wireless EEG amplifier and dry electrode headband which are developed by ourselves. From the preliminary testing results, physiological signals of high quality can be obtained by the designed system. The device is able to automatically detect drowsiness in **real time** and alarm in case of drowsiness occurrence. The real time processing is possible with the proposed algorithm. For our future work, some other improvements will be required, e.g. physical properties (weight and size of the device) and the detection algorithm with higher analytic techniques.

ACKNOWLEDGMENT

This work is supported in part by the national research university (NRU) funding of Mahidol University. We would like to acknowledge all Brain-Computer Interface Laboratory (BCI Lab) members for their support and Prof. Manoon Leechawengwong, M.D. for his useful assumption and comments.

REFERENCES

[1] J. Connor, G. Whitlock, R. Norton *et al.*, "The role of driver sleepiness in car crashes: a systematic review of epidemiological studies," *Accid Anal Prev,* vol. 33, no. 1, pp. 31-41, Jan, 2001.
[2] S. K. Lal, and A. Craig, "A critical review of the psychophysiology of driver fatigue," *Biol Psychol,* vol. 55, no. 3, pp. 173-94, Feb, 2001.
[3] A. Picot, S. Charbonnier, and A. Caplier, "On-Line Detection of Drowsiness Using Brain and Visual Information," *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on,* vol. 42, no. 3, pp. 764-775, 2012.
[4] T. Pilutti, and A.G. Ulsoy, "Identification of driver state for lane-keeping tasks," *American Control Conference, 1997. Proceedings of the 1997* vol. 5, pp. 3370-3374, 4-6 Jun, 1997.
[5] A. Picot, S. Charbonnier, and A. Caplier, "Monitoring drowsiness on-line using a single encephalographic channel," *in Recent Advances in Biomedical Engineering. Rijeka, Croatia: IN-TECH*, pp. 145-164, 2009.
[6] F. Sgambati, "Driver Drowsiness Detection," *Robert Bosch LLC*, January 26 2012.
[7] Ford Motor Company. Feb 11, 2012; http://www.ford.com.
[8] Volkswagen AG. Feb 11, 2012; http://www.volkswagen.com.
[9] Toyota Motor Corporation. Feb 11, 2012; http://www.toyota.com.
[10] B. T. Jap, S. Lal, P. Fischer *et al.*, "Using EEG spectral components to assess algorithms for detecting fatigue," *Expert Systems with Applications,* vol. 36, no. 2, pp. 2352-2359, Mar, 2009.
[11] Y. Punsawad, S. Aempedchr, Y. Wongsawat *et al.*, "Weighted-frequency index for EEG-Based mental fatigue alarm system," *International Journal of Applied Biomedical Engineering,* vol. 4, no. 1, pp. 36-41, 2011.
[12] P. P. Caffier, U. Erdmann, and P. Ullsperger, "Experimental evaluation of eye-blink parameters as a drowsiness measure," *European Journal of Applied Physiology,* vol. 89, no. 3-4, pp. 319-325, May, 2003.
[13] G. Dornhege, J.d.R.M., T. Hinterberger *et al.*, *Toward Brain-Computer Interfacing*, United States of America: Massachusetts Institute of Technology, 2007.
[14] S. Sanei, and J. A. Chambers, *EEG Signal Processing*, Cardiff University, UK: Centre of Digital Signal Processing, 2007.