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Development of a Smart Sleep Mask with Multiple Sensors

Bing Dang*, John Dicarlo, Stanislav Lukashov, Nigel Hinds, Jenna Reinen, Bo Wen, Tian Hao, Erhan Bilal, and Jeff Rogers

Senior Member, IEEE

Abstract— **In this work, we demonstrated a Smart Sleep Mask with several integrated physiological sensors such as 3-axis accelerometers, respiratory acoustic sensor, and an eye movement sensor. In particular, using infrared optical sensors, eye movement frequency, direction, and amplitude can be directly monitored and recorded during sleep sessions. We also developed a mobile app for data storage, signal processing and data analytics. Aggregation of these signals from a single wearable device may offer ease of use and more insights for sleep monitoring and REM sleep assessment. The user-friendly mask design can enable at-home use applications in the studies of digital biomarkers for sleep disorder related neurodegenerative diseases. Examples include REM Sleep Behavior Disorder, epilepsy event detection and stroke induced facial and eye movement disorder.**

Clinical Relevance— **Many diseases such as stroke, epilepsy, and Parkinson's disease can cause significant abnormal events during sleep or are associated with sleep disorder. A smart sleep mask may serve as a simple platform to provide various physiological signals and generate clinical meaningful insights by revealing the neurological activities during various sleep stages.**

I. Introduction

Sleep is an essential part of our lives because it facilitates many vital functions such as body energy conservation, cellular restorative processes, modulation of immune responses, and retention of brain memory, etc [1]. During a typical nightly sleep, our brain cycles through non-REM (rapid eye movement) and REM sleep several times. In particular, during REM sleep, our eyes move and dart quickly beneath eyelids accompanied with increased brain activity, faster pulse rates, as well as occurrence of dreams. REM sleep is very important to our sleep cycle because it can stimulate the areas of our brain for learning and memory [2-3]. Research studies show that the brain activity levels are similar to when we are awake during REM sleep, although body usually become temporarily paralyzed and major muscle controlling arms and legs cannot move. When REM Sleep Behavior Disorder (RBD) occurs, patients can physically act out vivid dreams through erratic and violent arm and leg movements. Such disorder can occur suddenly and affect a person's sleep several times a night [4].

RBD is usually diagnosed by a clinical history of dream enactment accompanied by polysomnographic rapid eye movement sleep atonia loss (rapid eye movement sleep without atonia). Recent studies revealed that RBD is strongly associated with neurodegenerative disease. For instance, a history of RBD may begin long time before the onset of any clear daytime symptoms of motor and cognitive impairments for diseases such as Parkinson disease, dementia with Lewy bodies, and multiple system atrophy [5-7].

Other common sleep related diseases include epilepsy and stroke. For example, studies showed that more than a half of the patients with epilepsy were diagnosed with sleep-related diseases. Epileptic population had significantly lower efficiency of sleep, had more N2 nonrapid eye movement (NREM) sleep, and had less rapid eye movement (REM) sleep with prolonged latency to REM sleep in comparison to general population [8]. As for stroke patients, several research studies show that Sleep-disordered breathing (SDB) and sleep-wake disturbances (SWD) increase the risk of stroke in the general population and affect short-and long-term stroke recovery and outcome [9-12].

Since the REM sleep was discovered, sleep researchers have relied on combination of electromyogram (EMG), electrooculogram (EOG), The electroencephalogram (EEG) to comprehensively observe the features of sleeping stages. Over the past decades, the understanding of the mechanisms and functions of rapid-eye-movement (REM) sleep have significantly advanced with the help from new neuroscience tools, which enabled high-precision interrogation of brain circuitry linked with REM sleep control [2,3,13]. Based on these ample research results, Polysomnography (PSG) has been developed and long been the "gold standard" for sleep measurement, in which total sleep time (TST) and sleep efficiency (SE), as well as specific sleep stages are recorded and measured in clinical settings [14, 15]. However, up to today, due to the complexity of monitoring system, clinical PSG is still costly, difficult to apply, and can be intrusive to sleep itself.

Recently, various consumer grade personal health monitoring devices have become available and offered potential to improve feedback and motivation in general health. For examples, several wearable EEG devices such as Muse hand-band and Philips SmartSleep are now commercially available, which may be used for sleep staging correlation. In addition, many bed sensor products are also available, which can provide several measurements such as heart rate, respiration, stress level, body movement, etc. Commercial product examples include Resmed, Earlysense, Emfit, Withings. As a result, research efforts have been made to validate these home-use devices to provide sleep measurements comparable to PSG as these devices are inexpensive, non-intrusive, and do not require a sleep technician for application. However, studies indicate that reliability of these consumer grade devices for sleep measurement depends on the measure of interest and application. While total sleep time and sleep efficiency (in some cases) can be simply monitored by these consumer grade devices, they do not yet yield sufficient information for accurate sleep staging, let alone for clinical applications such as detection of apneic events, REM sleep disorder, etc. [15].

As the sleep-detecting algorithms and measurement techniques continue to advance, consumer electronics-based systems may become more promising to offer home-use sleep monitoring and measurement with better accuracy and more insights to real-life sleep states. In this study, a Smart Sleep Mask is proposed and demonstrated with several integrated physiological sensors. In particular, using infrared optical sensor arrays, eye movement direction, magnitude and frequency can be directly measured and recorded during sleep sessions. Other signals such as 3-axis accelerometer, temperature, respiration sound, are also be available with synchronized measurement. Aggregation of these signals from a single wearable device may offer ease of use and more insights for sleep monitoring and REM sleep assessment.

II. Smart Sleep Mask Design

The key electronic components in our prototype design are shown in the Figure 1. A microcontroller with Bluetooth module is placed at the front side of the smart mask along with A 1000 mAh rechargeable battery, which can support all the electronics for continuous recording for more than 10 hrs. On the back side of the sleep mask, several sensors are integrated. At the center, a high sensitivity microphone is used as the acoustic sensor to monitor the respiratory sound along the nasal cannel. Toward the top side, there is a 3-axis accelerometer to detect the head motion and position during sleep. In addition, an eye motion sensor is placed in the recess space at the left side to detect any eye movement activities during sleep.

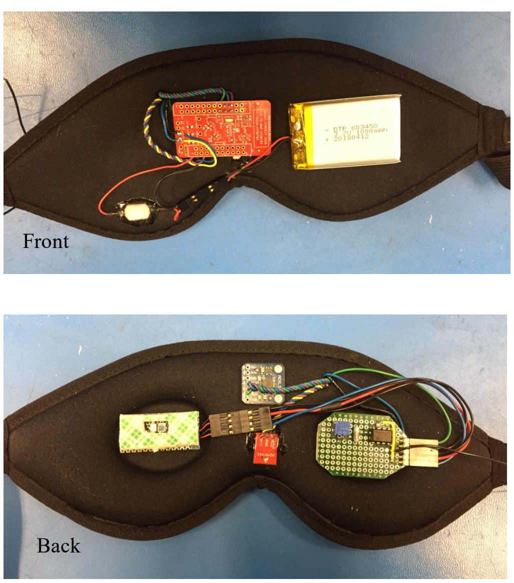

Figure 1. Images of front side and back side of the prototype smart sleep mask with sensors.

Our initial attempt to detect eye movement is to use a piezoelectric vibration sensor, which is sensitive enough to detect slight eye movement under the eye lids. However, it requires that the surface of the eye lids is in tight contact with sensor. Unfortunately, we quickly learned that it is not practical to keep the sleep mask in contact with eye lids during sleep as users may sleep with various head positions. In order to address this problem, an IR optical sensor has been evaluated and implemented successfully. As shown in the Figure 1, all sensors are wired to an amplifier board is placed at the right side of the sleep mask and signals are feed into the microcontroller with Bluetooth module.

In order to improve the comfort of wearing, an additional soft sleep mask is sewed over the sleep mask to cover those electronic components. Only the area in front of eyes is cut out for the eyes to be exposed to the sensors, as shown in Figure 2. Based on initial testing, the signals from a single optical sensor are prone to noise. Therefore, an improved optical sensor design with differential signals from two sensors has been proposed, which greatly improves signal-to-noise ratio. Figure 2a shows that two IR optical sensors with fixed distance of ~ 20 mm are used and a small IR light is placed between them. As the IR light is projected toward the eye lid, intensity of infrared light reflected from the eye lid can be measured separately on the two sensors. As an eye moves under its eye lid, the differential signals are generated due to resulted deformation and/or deflection of the eye lid. Furthermore, a quad-sensor design has also been tested, as shown in Figure 2b, which enables the measurement of the amplitude of eye movement in both horizontal and vertical directions. Based on the frequency and timing information, such a design can lead to precise characterization of eye movement under an eye lid.

(a). Dual optical sensor design

(b) Quad optical sensor design

Figure 2. Improved sleep mask design with more comfort user interface and (a) two optical sensors (b) 4 optical sensors.

III. Head Position Sensing and Classification

In order to comprehensively characterize and understand sleep condition for individuals, it is important to understand their head position as people naturally change their sleeping positions during sleep. Another important signal is respiratory sound because many acoustic events such as snore, cough, tooth grinding, even dream talking can occur during sleep. Therefore, 3-axis accelerometer and high sensitivity microphones are integrated in the sleep masks for continuous monitoring.

Figure 3 shows raw data from the microphone and the 3-axis accelerometer on the sleep mask. The sampling rate is adjustable and typically is set around 10 Hz. The acoustic sound may be used to detect respiratory events such as cough, snore and the 3-axis accelerometer signals can be used to detect head movement events as well as head position.

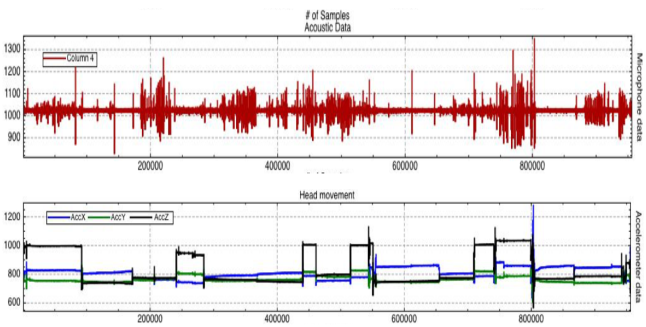

Figure 3. Raw data of acoustic sensors and accelerators.

Based on the relative values of accelerometer in x, y and z directions, the head positions can be classified as face up, face left, or face right for a person laying down on bed. Since typical head movement involves the turning along the neck axis (y-axis), the changes in the acceleration value in y-axis is less significant than those in x-axis and z-axis. Therefore, acceleration value in x-axis and z-axis can easily indicate the head position and movement events for a person wearing such a sleep mask. Figure 4 shows an example of calibration test to classify the head positions based on the relationship of the 3-axis acceleration values. It can be seen that the events and head positions can be labeled cleanly.

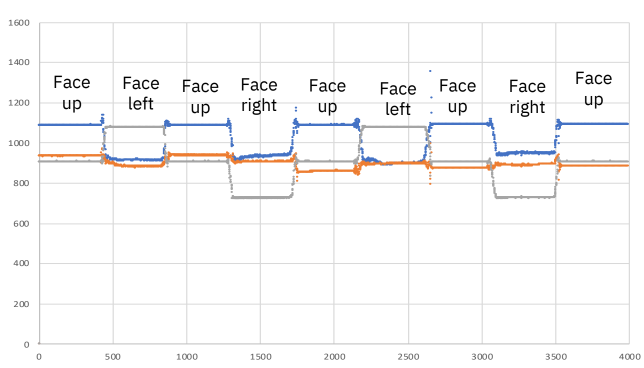

Figure 4. Classification of head position using 3-axis accelerometer data

IV. Eye Movement Signal Classification

As discussed in the introduction section, eye movement is one of the most important signals for sleep stage measurement. In traditional PSG settings, EOG is used for eye movement measurement, in which two electrodes are used (one is placed 1 cm above the outer canthus of the right eye and one is placed 1 cm below the outer canthus of the left eye) [14]. As the electro-potential between the front (the cornea) and the back (the retina) of the human eye is measured, the eye movement is estimated to determine when REM sleep occurs with reference of EEG signal patterns. In this work, our sleep mask with optical sensors provides a more straightforward sensing method to detect eye movement.

For instance, as a person blinks his/her eyes, the reflected IR light intensity from the two optical sensors will change accordingly. The differential amplifier will output significant changes in the output voltage values. Such a differential signaling method can help improve the signal-to-noise ratio and reduce output data stream size. Figure 5 shows an example of signals from the optical sensors in response to a series of blinking events. Significant changes can be distinguished on the IR sensor output voltage values.

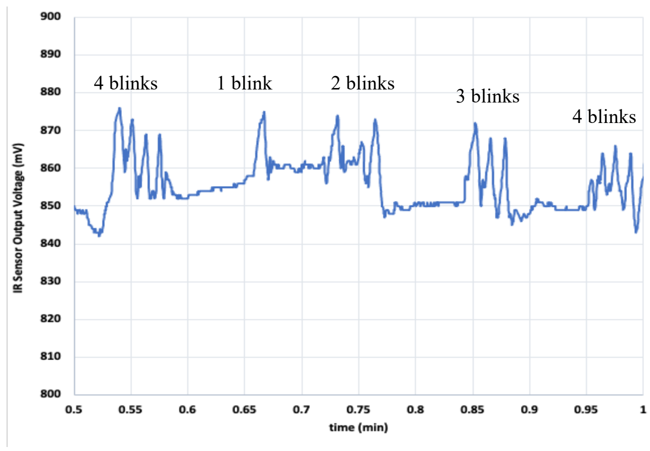

Figure 5. Example of eye activity detection by optical sensor signals.

Although dual sensor design is sufficient to detect eye movement events, the information from these its signals is not enough to characterize how an eye is moving. Therefore, we further investigated a quad sensor design, which uses a pair of optical sensors in horizontal direction and a pair of optical sensors in vertical direction. With two pairs of sensors, the sleep mask can output two sets of eye movement signals for each eye for more accurate characterization.

In order to demonstrate feasibility of eye movement characterization, we conducted calibration testing. During each calibration session, the subject performed a series of eye movement with eye lids closed with their best efforts, as described in Figure 6. The sequence includes the following actions: 1. eyes centered; 2. eyes to look up; 3. eyes centered; 4. eyes to look right; 5. eyes centered; 6. eyes to look down; 7. eyes centered; 8. eyes to look left; 9. eyes centered.

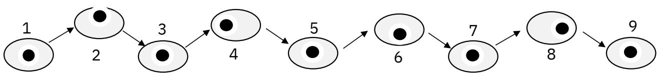

Figure 6. A sequence of eye movement for sensor calibration: 1) eyes centered; 2) eyes to look up; 3) eyes centered; 4) eyes to look right; 5) eyes centered; 6) eyes to look down; 7) eyes centered; 8) eyes to look left; 9) eyes centered.

The measured quad-sensor signals are recorded for several sessions and summarized in Figure 7, where blue lines are from sensors in vertical direction and red lines are from sensors in horizontal direction. When the subject performs the sequence of eye movement described above, the measured differential voltage in the vertical direction changes differently from the measured value in the horizontal direction. The pattern of eye movement in x-y coordinate can be measured and monitored with these two streams of signals with mathematical calculation and data visualization, which will be reported separately in future publication. As shown in Figure 7a – Figure 7c, the pattern of the data from 3 sessions repeats well, although it is not easy for the subject to precisely perform same eye movement in each session due to eye muscle fatigue.

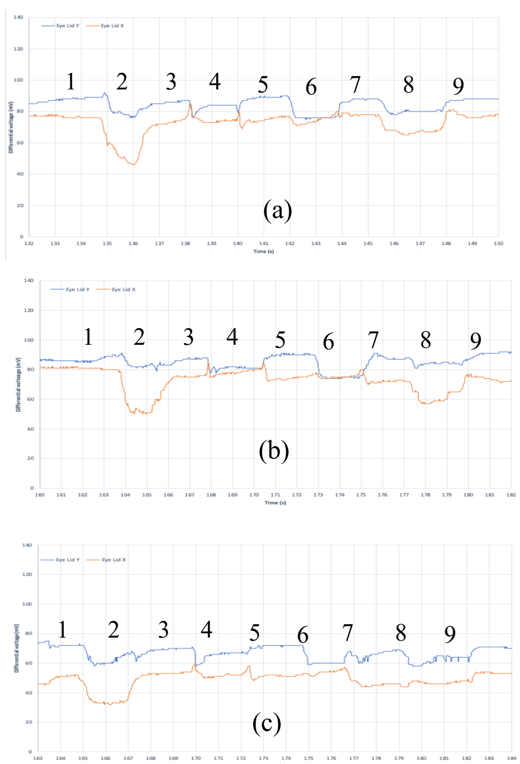

Figure 7. Differential voltage measured from two pairs of optical sensors in horizontal direction and vertical direction for 3 sessions of eye movement calibration.

V. Preliminary Testing for Real Life Sleep Sessions

While more signal analysis is being studied to better understand how to correlate the differential signals from the optical sensors with eye movement, we have performed several tests for real life sleep sessions. Figure 8 shows an example of optical sensor signals recorded on a subject during a day-time nap sleep session of ~40 mins. It is interesting to see that the amplitude and frequency of eye movement changes as the subject transits from the state of "awake" to "deep sleep". At the first 6 mins, the eye movement is very active because the subject is still awake. After the subject falls asleep, the eye movement activities clearly slowed down, which is consistent with the "slow wave" sleep in literature. After 25 mins, significant eye movement events with high frequency and amplitude become noticeable although the subject was still sleeping. This may be associated with REM sleep characteristics. Although such data is still very preliminary and more experiments are needed for validation, the data trending indicates that this technology may potentially be applied to sleep stage measurements based on direct monitoring of eye movement events and measurement of the eye movement amplitude and frequency.

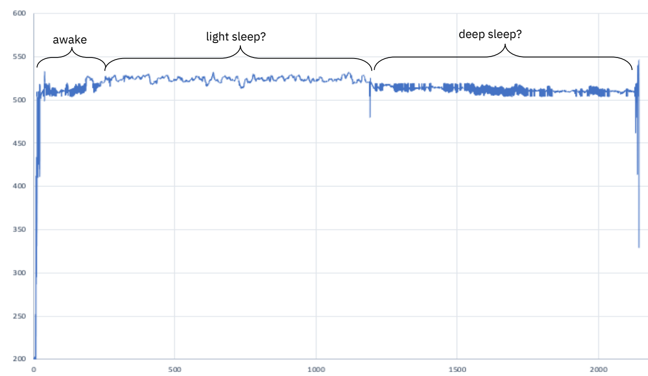

Figure 8. Example of continuous optical sensor signals for a day-time nap sleep session.

VI. Conclusions

In this work, we presented a smart sleep mask that incorporates a set of sensors for collection and aggregation of physiological signals. A mobile app has been developed for data storage and analytics. Such a device is relatively easy to deploy and promising to continuously monitor a variety of signals including head position, head temperature, respiratory sound, as well as the eye movement events for users with concern of sleep disorder or related diseases. Basic sensor signal processing and classification have been performed for head position and eye movement events. The preliminary tests on real life sleep sessions show a promising capability to distinguish eye activities during various phases of sleep.

VII. Acknowledgement

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