Chapter 1. Introduction

1.1 An introduction to sleep

Sleep is a basic physiological need of all humans and is characterized by a reduction in voluntary body movement and decreased reaction to external stimuli. Some early theories saw sleep as an intermediate state between awakeness and death [MacNish, 1834]. With the improvement of electrophysiological techniques, specifically the electroencephalogram (EEG), it was determined that the brain is not inhibited during sleep. Sleep is now seen as a unique state of consciousness. Dr. Nathaniel Kleitman, now known as the “Father of American sleep research,” described sleep as a periodic temporary cessation, or interruption, of the waking state, which is the prevalent mode of existence for the healthy human adult [Kleitman, 1939].

Scientists divide sleep into REM (rapid eye movement) and 4 NREM (non-rapid eye movement) sleep stages. REM sleep accounts for 20~25% of total sleep time and is associated with dreaming. NREM sleep accounts for 75~80% of total sleep time and is further subdivided into light sleep (Stage I and Stage II) and deep sleep (Stage III and Stage IV). Sleep proceeds in cycles of NREM and REM phases. In humans, the cycle of REM and NREM is approximately 90 minutes.
There are many theories about the functions of sleep. Researches show that REM sleep and NREM sleep play different roles. Hartmann [1973] stated that deep sleep stage of NREM has a physically restorative function after exercise, injury, or physical tiredness and is related to anabolism and synthesis of macromolecules. On the other hand, REM sleep has a restorative function with focused attention and emotional adaptation to physical and social environment. Marks et al. [1995] pointed out that REM sleep is particularly important to the developing brain and is necessary for proper central nervous system. Studies investigating the effects of REM sleep deprivation have shown that deprivation early in life can result in behavioral problems, permanent sleep disruption, decreased brain mass [Mirmiran et al., 1983], and result in an abnormal amount of neuronal cell death [Morrissey, Duntley and Anch, 2004]. An increasing number of theorists showed a strong relationship between sleep and memory. [Siegel, 2001, Stickgold, et al., 2001, Gais and Born, 2004]. In summary, sleep is related with functional status, general and mental health. [Briones et al., 1996, Cauter, et al., 1999, Ashmana, et al., 1999, Meijer, et al., 2001]

Since the discovery of electrical brain wave activity by Hans Berger in 1929, the electroencephalogram (EEG) has become a clinical and diagnostic tool for brain dysfunction. By using the EEG, different stages of sleep were classified in 1937 [Loomis et al., 1937]. After discovery of the REM (rapid eye movement) sleep periods by Aserinsky and Kleitman in 1953 and the demonstration of periodical sleep cycles by Dement and Kleitman, polysomnography was established as the major diagnostic tool in sleep disorders [Aserinsky and Kleitman, 1953, Dement and Kleitman, 1957]. Sleep stage is currently evaluated based on the Rechtschaffen and Kales (R-K) method [Rechtschaffen and Kales, 1968].

A polysomnogram consists of a simultaneous recording of multiple physiologic parameters related to sleep and other physiologic disorders related to sleep. A polysomnogram usually has several channels include the following:

1. Electroencephalography (EEG): To evaluate sleep stage.
2. Electrooculogram (EOG): To monitor both horizontal and vertical eye movements.
3. Electromyography (EMG): To detect periodic limb movements of sleep
(4) Airflow, respiratory effort, sound, blood oxygen saturation (SaO2): To observe sleep-related breathing disorder, such as snoring and obstructive sleep apnea syndrome (OSAS).

(5) Other parameters: electrocardiograph (ECG), temperature, light and so on.

Due to the development of sensing technology, small, portable, non-conscious and tele-monitoring devices, are new approaches for sleep monitoring. Sleep-related breathing disorders, body movements, sleep stage and sleep quality are main research fields of sleep. These issues will be discussed in details in the following sections 1.2-1.5.

1.2 Sleep-related breathing disorder

Snoring is a very common problem and a possible sign of sleep-related breathing disorder. Intermittent snoring and drops of SaO2 are characteristic features of OSAS. In clinical practice, PSG recording is used as the standard evaluation procedure for sleep-related breathing disorder (SRBD). Patients have to wear SaO2 saturation, nasal airflow, thoracic effort, and sound sensors to do one-night tests in a specialized laboratory. Snoring and OSAS symptoms are identified by off-line diagnosis software in a computer.

Several computer-based systems have been developed to quantitatively measure snoring using acoustic sounds. Jane et al. [2000] designed an automatic algorithm for detecting acoustic snoring signals based on a neural network. The input pattern of the neural network, which consists of 22 temporal and spectral features of each sound segment, distinguishes between the snoring sound and other respiratory sounds. Figure 1-1 shows a snore recording with 500,000 data (sampling frequency 5000 Hz), 15 snorers of a normal snorer were detected. In their validation test, more than 500 snores were randomly taken from a database of 30 patients and analyzed. The average sensitivity of the algorithm was 82% and the average positive prediction value was 90%. Solà-Soler et al. [2005] used a logistic regression model to classify normal snorers and OSAS patients by observing their sound intensity and other spectral parameters. The model’s parameters were adjusted to correctly classify 100% of the OSAS patients at the expense of 57.1% of normal snorers.
Due to the development of microprocessor technology, some portable systems have been designed for monitoring snoring and OSAS. Cohen [1990] presented algorithms utilizing a microprocessor for the quantitative and objective analysis of acoustical pulmonary signals, such as breathing and snoring sounds. Penzel et al. [1990, 1991] developed a digital recording device, called MESAM IV (MAP; Martinsried, Germany) to monitor oxygen saturation, heart rate, snoring and body position in order to screen patients for the presence of OSAS. MESAM IV records snoring sounds by means of a laryngeal microphone. If the proportion of sounds between 50Hz and 800Hz exceeds 50%, it is assumed that patients are snoring. Intermittent snoring is defined as intervals between two detected snores that last between 5 seconds and 60 seconds. The diagnosis of OSAS was established by calculating oxygen desaturation index, heart rate variation index and intermittent snoring index. Following this development, a number of validation studies on MESAM IV were presented [Stoohs and Guilleminault, 1992, Koziej, et al., 1994, Esnaola, et al, 1996, Verse, et al, 2000, Cirignotta, et al., 2001]. In these studies, the intermittent snoring index was found to have high sensitivity (92%-96%) but low specificity (16%-27%). MESAM IV can record for periods of up to 18 hours, which makes it possible to perform examinations in a patient’s home environment and then to be diagnosed in the hospital.
Audio alarms and stimulators are widely used to stop snoring or apnea processes during sleep. Kermit et al. [Kermit, et al., 1995] developed a device for early online detection of upper airway obstructions. If an obstruction is detected, an audio alarm alerts the patient to prevent the occurrence of apnoeic events. Çavuşoğlu et al. [2005] also proposed a similar approach to alarm a patient when the voltage of a nasal air flow sensor was below the threshold value. Miki et al. [1989] reported positive results with electrical stimulation in patients with OSAS. In their research, when an apnea lasted more than 5 seconds, electrical pulses of 0.5 ms (repetition rate, 50 Hz) and 15 to 40 volts were delivered through bipolar electrodes attached to the skin. The electrical pulses stopped immediately after breathing resumed or after 10 seconds. As a result, the number of times per hour that oxygen saturation dropped below 85% decreased significantly. Guilleminault et al. [2002] also presented similar procedures with stimulations that started within 5 seconds of abnormal breathing and stopped with the resumption of normal breathing.

1.3 Body movements

During sleep, low motor activity levels and prolonged episodes of uninterrupted immobility are associated with increasing sleep depth. There are also motor disturbances that are triggered by sleep such as restless legs syndrome (RLS) and periodic limb movements during sleep (PLMS). Such symptoms disrupt sleep and cause daytime tiredness and sleepiness.

Several non-invasive and unrestrained sensing techniques have been developed for the monitoring of movement during sleep. The use of load cells or force sensors is the most common approach to detect movements on bed. Load cells represent a simple and durable technology, which is used in several researches [Wheatley, et al., 1980, Barbenel, et al., 1985, Choi, et al., 2004, Adami, 2005]. The use of force sensor is also a popular technique for monitoring movements in bed. Nishida et al. [1997] presented the idea of a robotic bed, which is equipped with 221 pressure sensors for monitoring of respiration and body position (Figure 1-2). Van der Loos et al. [2004] also proposed a similar system called SleepSmart™, composed of a mattress pad with 54 force sensitive resistors and 54 resistive temperature devices, to estimate body center of mass and index of restlessness.
These large-size equipments are not easy to set up and can be used in specific laboratories only.

Many pad-based solutions have been proposed. Several authors have employed the static charge sensitive bed (SCSB) for monitoring of motor activity. The SCSB is composed of two metal plates with a wooden plate in the middle that must be placed under a special foam plastic mattress, which operates like a capacitor [Alihanka and Vaahitoranta, 1979, Rauhala, et al., 1996, Kaartinan, et al., 2003]. Watanabe et al. [2005] designed a pneumatics-based system for sleep monitoring. A thin, air-sealed cushion is placed under the bed mattress of the subject and the small movements attributable to human automatic vital functions are measured as changes in pressure using a pressure sensor (Figure 1-3).

Figure 1-3. A pneumatics-based system for sleep monitoring [Watanabe et al., 2005]
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New sensing techniques, such as optical fibers and conductive fibers are also been used for monitoring of movement on bed. Tamura [1992] et al, proposed a body movement monitoring system using optical fibers. Kimura et al. [2004] designed an unobtrusive vital signs detection system, which uses conductive fiber sensors to detect body position, respiration, and heart rate. These fiber sensors can be incorporated in a conventional bed sheet for home use (Figure 1-4).

![Figure 1-4. An unobtrusive vital signs detection system, which uses conductive fiber sensors [Kimura et al., 2004]](image)

1.4 Sleep stage and sleep quality

Polysomnography is considered to be the “gold standard” for assessing sleep. Different sleep stages are evaluated by medical specialists using polygraph data such as electroencephalogram (EEG), electrooculogram (EOG), and electromyogram (EMG) based on the Rechtschaffen and Kales (R-K) method. This technique usually requires individuals to sleep in research laboratories which are known to change habitual sleep patterns [Reynolds, et al., 1992] and induce a “first-night” effect [Riedel, et al., 1998].

Behavioral response monitoring methods have been proposed for the evaluating of sleep/wakefulness [Bonato, et al., 1995, Blood, et al., 1997]. In the behavioral response monitoring paradigm, a threshold intensity visual or auditory stimulus generated by a
computer was presented about once per minute, and subjects pressed a microswitch if the stimulus was detected.

The relationship between heart rate variability and sleep stages has also been discovered. Ichimaru [1995] et al. observed that the RR-interval was shorter during REM sleep than during NREM sleep. Méndez [2006] et al. proposed a time-varying autoregressive model to separate the REM and NREM sleep epochs. Watanabe [2004] et al. designed a noninvasive and unrestrained pneumatic biomeasurement system, based on an air cushion and pressure sensor, to evaluate heart rate. In this system, sleep depth is given by linear functions of heart rate and the different between wake and REM sleep stages are discriminated by body movement data.

Since the development of the actioculographic monitor in 1979, a novel method to estimate sleep stage through body movements have been suggested. Measurement of motility has become a popular method in the study of human sleep. Kayed et al [1979] used three criteria, eye movements, body movements, and submental electromyogram, to identify awake, REM sleep, and NREM sleep (Figure 1-5). Based on this development, a wearable wrist actigraphy, have been developed for the identification of awake, REM and NREM stages [Hauri and Wisbey, 1992, Emilia, et al., 1999, Ancoli-Israel, et al., 2003]. Ajilore et al. [1995] proposed a home-based sleep monitoring system, called Nightcap, which uses eyelid and body movement sensors to discriminate wake, NREM, and REM sleep automatically. Literatures show that actigraphy is a valuable device to detect sleep-wake period between actigraphy and PSG ranging from 80% to 90% [Hauri and Wisbey, 1992; Sadeh, et al., 1995]. Although estimating sleep stages through body movement is not as accurate as PSG, studies are in general agreement that measures with body movement were fairly sensitive in detecting sleep.
Figure 1-5. Different body activity patterns of awake, N-REM and REM stages [Kayed et al., 1979]

Similar to wrist actigraphy, Choi et al. [2007] introduces a bed actigraphy for user-friendly sleep-wake monitoring (Figure 1-6). An automatic scoring algorithm scored each epoch of the recordings for either ‘wake’ or ‘sleep’ by the signals of 4 load cells, which are installed at each corner of the bed. Bed actigraphy has some advantages over ordinary actigraphic devices. First, the bed actigraphy does not constrain the subjects during recording. The subject can even be unaware of the recording process. Secondly, bed actigraphy can detect the overall movements of the subject by measuring the body activity at four points, while an actigraph detects only the movements of the body part on which it is mounted. The bed actigraphy shows good agreement (95.2%) but medium sensitivity and predictive value (64.4%, 66.8%).

Figure 1-6. The bed actigraphy system [Choi et al., 2007]
Sleep quality refers both the subjective assessment given by the subject of how restorative and undisturbed his/her sleep has been (via a standardized questionnaire) or to a series of objective measures (from self-report, wrist actigraphy monitoring, “Nightcap” monitoring, polysomnogram, etc.). The most commonly used measure of sleep quality is the Pittsburgh sleep quality index (PSQI), proposed by Buysse et al. in 1989. Nineteen individual items generate seven "component" scores: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction. The sum of scores for these seven components yields one global score of 1-21.

Peng et al. [2006] proposed a system which consists of heart-rate, video, and audio sensors, and apply machine learning methods to infer the sleep-awake condition during the time a user spends on the bed (Figure 1-7). The PSQI Scores of three objective components (sleep latency, sleep duration, and habitual sleep efficiency) can be estimated through the asleep/awake detection. Similar procedures, which estimate sleep quality with the PSQI via sleep-awake stages, are suggested by several authors [Aritomo, et al., 1999, Wakoda, et al., 2005].
1.5 Tele-monitoring and the PTMS structure

For the needs of remote monitoring of sleep, several research activities are underway. Kristo et al. [2001] presented a telemedicine protocol for the online transfer of PSGs from a remote site to a centralized sleep laboratory, which provided a cost-saving approach for the diagnosis of OSAS. Seo et al. [2005] developed a non-intrusive health-monitoring house system to monitor patients’ electrocardiogram results, weight, movement pattern and snoring, in order to get the information of patients’ health status and sleep problems. Choi et al. [2004] presented a ubiquitous health monitoring system in a bedroom, which monitors ECG, body movements and snoring with non-conscious sensors.

A centralized framework is used in most home tele-health systems, in which a centralized database is used for data storage and analysis. Figure 1-8 shows the structure of the “Portable Telehomecare Monitoring System (PTMS)” developed by the authors [Hsu, et al., 2007]. The PTMS is a decentralized home tele-health system. Instead of using a centralized database that gathers data from many households, a single household is the fundamental unit for sensing, data transmission, storage and analysis in the PTMS. The monitoring data is stored in the “Distributed Data Server (DDS)” inside a household.
As shown in Figure 1-8, sensing data from sensors embedded in the home environment are transmitted to the DDS. Sensing signals are then processed and stored in the DDS. Authorized remote users can request data from the DDS using an Internet web browser (through an application server) or a Visual Basic (VB) program (direct access to the DDS). Event-driven messages (mobile phone text messages or emails) can be sent to specified caregivers when an urgent situation is detected.

![Figure 1-8. The structure of the PTMS](image)

There are several advantages of the PTMS structure over the traditional centralized database structure:

1. The scale of the PTMS is much smaller, which makes it economically viable and acceptable to the end-users. A single household can be a running unit of the PTMS. This distributed structure can be adapted if a centralized database is needed.
2. Instead of sending the health monitoring data to a centralized database in a home health care provider, health monitoring data are stored within the household. Only authorized caregivers can access the data. Privacy is better protected.
3. The route from the sensor to server is much shorter. Data transmission is easier and more reliable. When the Internet communication fails, the local system can...
still function normally and keep collecting data. Thus data integrity is better preserved.

1.6 Purpose of this research

Significant research activities are underway in the development of sleep monitoring systems. However, a basic problem is that, it requires specialists with a high degree of technical expertise and the use of an expensive polygraph. Nowadays, small, portable, non-non-invasive, non-constrictive, non-conscious and remote monitoring techniques are new approaches for sleep monitoring at home.

This research describes the development of a tele-monitoring system for sleep (called the Sleep Guardian system) based on the PTMS structure. This system embraces a snoring and OSAS symptoms detector (SOD), a physical activity detecting system (PAD-Mat) and a sleep diagnosis interface. The Sleep Guardian system on-line monitors the symptoms of sleep-related disorders, such as snoring, OSAS, PLMS, and evaluates sleep stages and sleep quality via physical activity data. This portable monitoring system is to be used as a home appliance as a precautionary measure. Patients who are classified to have sleep disorders by the Sleep Guardian system should consult doctors for further diagnosis.

Figure 1-9 shows the structure of the Sleep Guardian system developed in this research. Similar to the PTMS structure in Figure 1-8, the core components of the SOD and PAD-Mat are DDSs which analyze bio-signals captured by sensors and classify symptoms by detecting algorithms. The DDS consists of a PIC server mounted on a peripheral application board. The PIC server integrates a PIC microcontroller (PIC18F6722, Microchip), EEPROM (24LC1025, Microchip) and a networking IC (RTL8019AS, Realtek). It provides networking capability and can be used as a web server. Users and caregivers can access the sleep guardian system for historical monitoring data via the Internet for further analysis. This tele-monitoring system provides a convenient approach to better understand and recognize sleep-related problems.
Figure 1-9. Structure of the Sleep Guardian system

The rest of this dissertation is organized as follows. Chapter 2 and Chapter 3 present the development of the PAD-Mat and the SOD. Chapter 4 proposes a network framework and a sleep diagnosis interface of the Sleep Guardian system. Chapter 5 describes the applications and benefit of the Sleep Guardian system.

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MacNish, R., The philosophy of sleep, 1834.


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and Biology Society, v.13, n.4, 1991,


