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SOMNUS: A SLEEP DIAGNOSTICS SHIRT EMPLOYING RESPIRATORY PATTERNS THROUGH CHEST EXPANSION

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ABSTRACT

This paper presents a shirt embedded with simple capacitive sensors that accurately monitors the respiration of a sleeping person through chest expansion. It will also discuss a software package that, when coupled with this device, can determine sleep stages from the acquired data. Current sleep studies are the only medically accepted form of sleep health detection and diagnosis; due to the relatively high price of these studies, only persons with breathing-related disorders are referred to them. These studies depend on polysomnography, the use of various bodily signals for sleep detection; patients are often connected to over twenty sensors ranging from brain wave electrodes to blood oxygen trackers. The Somnus shirt is a comfortable, low-cost solution that could be used in the patient's regular sleep setting. Through some preliminary testing, our respiration-monitoring prototype was able to produce respiration data similar to that of sensors employed in current sleep labs while achieving a higher level of comfort for the user; also, the software package was able to analyze sleep with accuracy comparable to current sleep laboratory technicians.

1 INTRODUCTION

According to the National Institute of Neurological Disorders and Stroke, over 60 million Americans suffer from insomnia on a regular basis [1]. Unfortunately for this percentage of the population, emphasis has been placed on drug treatment rather than prevention. A lack of budget-friendly alternatives to current studies for accurate sleep health monitoring leaves this sleep disorder undiagnosed. Sleep studies are inherently expensive because of their employment of polysomnography (PSG), which, while critical for detection of various sleep disorders, is extremely costly. A paid technician must monitor patients at all times and score each test manually afterwards, adding to the expense.

In addition to price, laboratory testing is also disruptive to the regular sleep routines of the average patient. Patients are asked to sleep away from their homes, in a different bed, and wearing an array of electrodes and bands. This makes for a less-than-perfect test, as comfort could potentially directly affect sleep quality. Somnus aims to resolve both of these issues by accurately monitoring sleep health while allowing the wearer to sleep virtually anywhere he or she normally does. The shirt utilizes embedded, capacitive sensors to accurately measure the respiration rate of a person throughout the night. This system is comprised of a co-planar plate capacitor connected to an electronics package that allows for data gathering and transmission. The data can then be fed through the analysis software to determine sleep staging. Unlike traditional sleep studies, the device can achieve a level of comfort much closer to what users are accustomed to, making sleep analysis more practical and potentially more accurate. The software also has the ability to analyze a night's sleep in less than a minute, and, given the low costs of the materials, could potentially make for a budget-friendly option to consumers who cannot currently afford a sleep study.

2 BACKGROUND

2.1 Medical Sleep Studies

In 2001, a study found that 1291 sleep laboratories conducted over a million polysomnographs in the US alone [2]. Current sleep staging techniques employ PSG because of the complexity and range of neurological and physical sleep disorders. Regular sleep staging procedures vary, but most employ respiration, electroencephalography (EEG), and electromyography (EMG) data.

Except in rare cases, PSG must be conducted inside a sleep laboratory. Subjects must be instrumented with over 20 sensors - over a dozen on the head to measure EEG and muscle movement around the eye, two for air flow in and around the mouth and nose, one on the leg for EMG, two respiration belts, and three electrodes for measuring heart rate. These form a large bundle that is not only uncomfortable, but restricts the motion of the patient. Once the night is over, a technician examines the data and, using the various signals, creates a hypnogram showing a summary of sleep stages. A study by Suzuki et al has shown that technician scoring is objective; test results from 16 scorers determined that the rate of coincidence among the staging results was just over 70% [3].

2.2 Alternative Approaches

Some at-home devices have entered the medical sleep monitoring industry, but most are still too uncomfortable or unreliable to be employed for medical diagnosis [4]. While PSG is the current standard for sleep staging, respiration has been found to be a good marker for wakefulness and rapid eye movement (REM) stages, making it also easy to detect whether a person is in light or deep sleep (non-REM stages) [5, 6]. Current methods for determining respiration include using wireless, range-finding devices that detect changes in the distance to the patient's chest [7]. However, these methods require special apparatuses to be installed and are dependent on the positioning of the patient within the range detector's field of view. Other methods use pressure sensors placed under the patient's mattress [8]. Systems of these types require the patient to be in a supine position and any changes to this position can cause the systems to fail to record respiration data.

3 SENSOR DESIGN

Both resistive and capacitive properties have proven successful at detecting respiration [9, 10]. Preliminary concept designs led towards a simple approach that detected strain in a tight-fitted shirt due to the expansion of the chest.

3.1 Coplanar Plate Model

In order to sense the change in respiration, the device uses two coplanar plates, with a small gap between them as shown in Figure 1, configured to act as a capacitor.

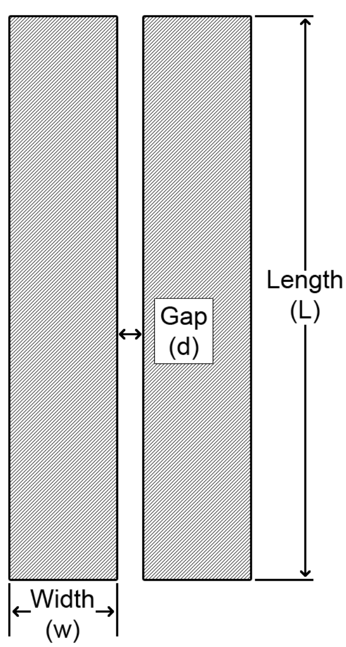

FIGURE 1: CO-PLANAR PLATE CONFIGURATION

The capacitance between these two plates is given by Equation 1 [11].

$$C = \varepsilon L \frac{K\left(\sqrt{1-k^2}\right)}{K(k)} \quad (1)$$

where ε is permissivity, $K(x)$ is the complete elliptic integral of the first kind, and k is given by Equation 2.

$$k = \frac{d}{2w+d} \quad (2)$$

In order to validate this model, the measured capacitance of two sets of plates, both in stretched configuration and un-stretched configuration, was compared with the theoretical results. Figure 2 shows this comparison. In addition to confirming the model, the figure shows that in the viable range of operation, the change in capacitance is approximately linear.

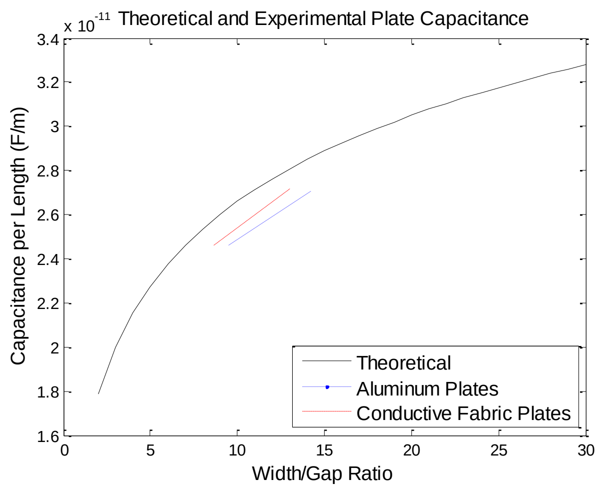

FIGURE 2: COMPARISON OF THEORETICAL AND EXPERIMENTAL PLATE CAPACITANCE

3.2 Pad Design

The device is composed of an Underarmour HeatGear form-fitting shirt with two conductive ink pads painted onto a substrate, which is laid directly onto the cloth. These pads are embedded into the fabric of the shirt to form a co-planar plate capacitor with a small gap of elastic fabric between them. As the subject's chest expands, the size of the gap increases, causing a decrease in the capacitance between the two plates. The respiration sensors can be placed at intervals around the shirt to ensure continuous respiration recording even when the patient shifts during the night and prevents a given pad from operating. It is also important to note that various patients breath differently. Expansion of the abdomen and the lower chest can differ from patient to patient, and the design allows for all breathing patterns to be accommodated. Figure 3 shows the final prototype with three locations: a chest sensor and two side abdomen sensors.

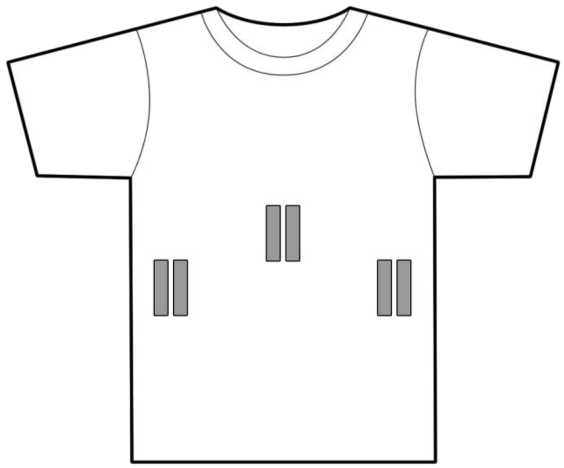

FIGURE 3: SHIRT WITH THREE SENSORS: ONE CHEST SENSOR AND TWO ABDOMEN SENSORS.

3.3 Capacitive Detector

To measure the change in capacitance between the two plates, an AC signal is passed through an op-amp based comparator that evaluates the sensor capacitance against a known reference capacitor. This circuit converts a change in relative capacitance between the respiration sensor and the reference into a change in voltage, which can then be recorded using any commercial data logger.

In addition, a Bluetooth connection was developed to stream live respiration data to recording software that can display the data in real-time. This allowed the patient to be monitored remotely without disrupting his or her sleep and for data to be stored remotely.

4 SOFTWARE DESIGN

A typical polysomnograph can take up to three hours to grade by a trained technician, a method of manual scoring that is costly and inefficient. In order to create the Somnus sleep package it was necessary to devise an automated method to quickly and accurately score a patient's sleep.

4.1 Preliminary Analysis

Because patients of different sizes and different conditions will have varying amounts of chest expansion during respiration, it was necessary to develop a tool that is independent of the magnitude of strain. Instead of analyzing amplitude changes of the chest, emphasis was placed primarily on the frequency of its movement and any indicators exhibited by it.

Data analysis begins with the duplication and time shift of the original respiration data showing amplitude and time. After this manipulation, single breathing periods are detected whenever the two data sets cross. Since typical respiration may exhibit sudden changes in direction whenever the chest is fully expanded or contracted, there can be small errors in beat detections if the data is not properly shifted. To correct this, the duplicated data is re-shifted by the average period length and the process is repeated. After finding these corrected breathing periods, a matrix is created indicating the start of each breath.

To build an accurate model of breathing volatility over time, the software runs small samples of this data through a fast Fourier transform (FFT). The optimal window size was found, though testing, to be 3-5 breathing periods. Each individual FFT yields three data points that are used to build a Stability Index (SI) for this window. The frequency with the largest intensity, shown below as point A in Figure 4, is the dominant frequency in the FFT. The relative intensity of the dominant frequency, point B in Figure 4, represents the periodic nature of the breathing in this window. Lastly the width, or bandwidth, of the dominant frequency peak, shown as C in Figure 4, acts as a third indicator of stability. Because the frequency peak of the FFT is typically at a very low frequency, the run time is decreased by simply setting the bandwidth equal to the frequency corresponding to 0.5% of the peak intensity.

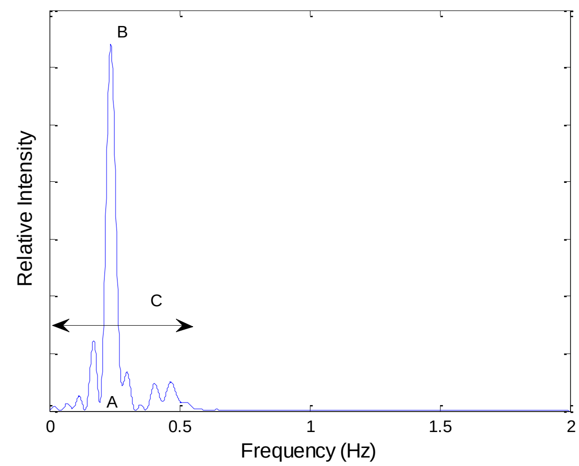

FIGURE 4: FAST FOURIER TRANSFORM OF RESPIRATION WINDOW

It has been found that an instantaneous categorization of a respiration window alone is not satisfactory for determining its corresponding sleep stage; therefore, the SI cannot be solely used for staging. A Time Index (TI) is then determined based on the relative change in the SI over various windows. This method collects five consecutive SI samples and determines the mean change between them. This index exhibits how quickly the breathing frequency is changing, the stability of the dominant frequency, and the time-variance of the bandwidth.

4.2 Staging

For the software to be useful, an accurate sleep staging hypnogram must be produced. An algorithm in the software uses both the SI and TI to determine a window's corresponding sleep stage. The algorithm first determines if the patient is awake by checking for both unstable breathing and rapidly changing intensity of the dominant frequency. These areas of wakefulness are determined when the stability's magnitude is less than its change. By subtracting the TI from the SI, it is possible to quickly determine awake periods with a simple negative threshold.

Next, the algorithm scores periods when the patient was in stable, non-REM sleep. It was found that during this stable stages the intensity of the dominant frequency maintains a large, steady value. In addition, both the time-averaged change in intensity and the dominant respiration frequency drop. By setting thresholds based on the mean difference between the SI and the TI, as well as the average respiration rate, it is possible to reliably find periods of stable sleep. Currently the algorithm does not differentiate between the different non-REM stages, and, while this is a problem for diagnosing various sleep disorders, it should be possible to further develop a method to classify the various levels of non-REM sleep by comparing the relative level of intensity of the dominant respiration frequency.

Finally, the algorithm finds periods of REM in periods of stable sleep. To accomplish this, the algorithm looks for periods when the time-averaged change of the respiration is greater than a certain threshold. These periods represent stable respiration with a rapidly changing frequency. A small flaw is recognized in this method of determining REM in that the algorithm only looks for REM within periods of stable sleep and does not recognize periods where a patient drops between wake and REM quickly. This can be resolved by creating a REM threshold that includes periods of wake as opposed to only stable sleep periods.

4.3 Visual Tools

Besides the standard sleep staging hypnogram that is commonly used, two additional visual tools were created to help quickly categorize a patient's sleep. First, a sleep Heat Map is built directly from the FFTs and is shown below in Figure 5. The image shows frequency over time with intensity indicated by color.

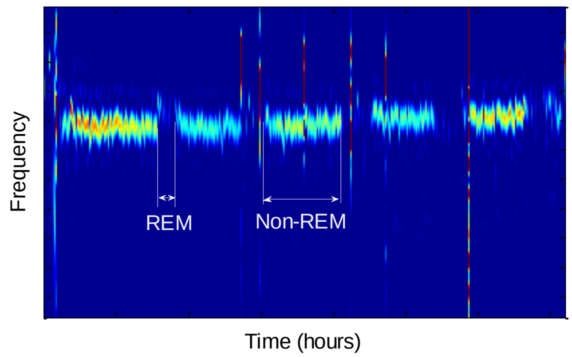

FIGURE 5: SLEEP HEAT MAP WITH HIGH INTENSITY (RED) AND LOW INTENSITY (BLUE)

It is easy to identify stable non-REM sleep periods indicated by bright areas on the Heat Map representing strong, stable respiration. It is also easy to identify REM, indicated by gaps of darker blue when the respiration frequency becomes more variable. Awake periods stand out as taller bands with a darker red color as the respiration exhibits a more randomness. The second visual aid consists of a Frequency Stability Graph show below in Figure 6.

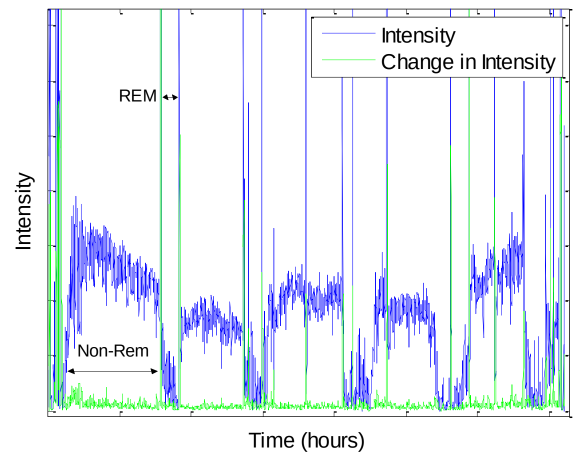

FIGURE 6: FREQUENCY STABILITY GRAPH

The Frequency Stability Graph helps to further analyze the relative depth of sleep. Shown on the graph are both dominant frequency intensity and time averaged change in intensity vs. time. Periods of stable sleep show up again as a rise in dominant frequency intensity and REM stages can be categorized when the relative intensity drops to the level of the change of intensity.

5 DEVICE AND SOFTWARE VALIDATION

5.1 Sensor Test Setup

In order to validate the shirt's ability to accurately detect a clean respiration signal, a prototype test was conducted in which a subject was asked to sleep while being monitored both with the Somnus sleep package and the traditional sleep study sensors. Due to restrictions in the sleep lab as well as the need for only a small amount of respiration data, the test was conducted for a short amount of time during the late afternoon. The test subject consisted of a healthy 21-year-old male with no known sleep disorders. The Somnus sleep shirt was connected to a Bluetooth device that transmitted data to an adjacent room during the test. This allowed for continuous monitoring in case of hardware complications. A data logger in parallel maintained a copy of the respiration data, and, after over two hours of continuous data collection, the subject was awoken. Shown in Figure 7 is a sample of the respiration data gathered from the Somnus shirt.

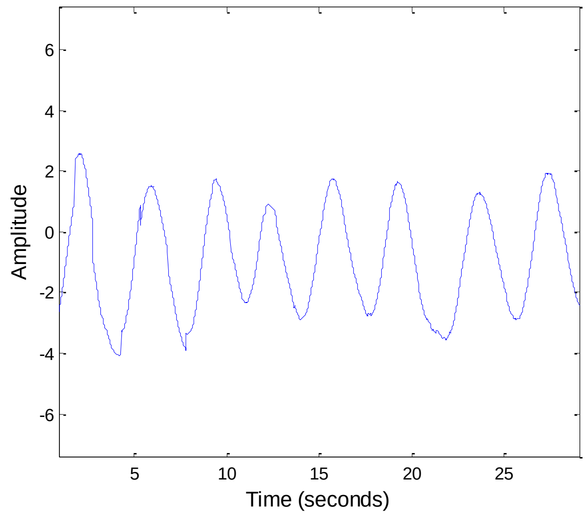

FIGURE 7: SOMNUS RESPIRATION DATA

The Somnus shirt was able to gather a clean respiration signal from the subject. With a small amount of post processing a nearly identical respiration signal was achieved. While the measured amplitude was smaller than the data from the standard inductive belt, the relative magnitudes were the same and the difference can easily be corrected with an additional amplifier stages.

5.2 Software Test

To validate the automated sleep scoring method, data from existing sleep studies was gathered. The data was parsed and only a single respiration channel was used in addition to a technicians scoring of each study. The algorithm was tested with each study and the output hypnogram was compared to that of the technicians by % time spent in both NREM and REM stages of sleep. The algorithm correctly scored each study with 70%-80% accuracy, which is comparable to that of a technician, while having the advantage of being completely repeatable.

6 CONCLUSION AND FUTURE WORK

The Somnus shirt was successful in monitoring a patient for an extended period of time; furthermore, the software was able to conduct simple sleep staging and to derive stability graphs that could be useful for future medical diagnosis of sleep. Moving forward, further sensor materials and production techniques must be explored. Additionally, hardware solutions, as well as their integration into the shirt, will be considered. Further testing can be conducted once a beta prototype with fully-embedded electronics is finalized; software testing can continue with further collaboration from sleep study facilities in order to fully validate the accuracy of the staging algorithm.

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