

A Non-invasive Wearable Neck-cuff System for Real-time Sleep Monitoring

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Abstract—Sleep is an important part of our lives which affects many life factors such as memory, learning, metabolism and the immune system. Researchers have found correlations between sleep and several diseases such as Chronic Obstructive Pulmonary disease, Chronic Heart Failure, Alzheimer’s disease, etc. However, sleep data is mainly recorded and diagnosed in sleep labs or in hospitals for some critical cases with high costs.

In this work we develop a non-invasive, wearable neck-cuff system capable of real-time monitoring and visualization of physiological signals. These signals are generated from various sensors housed in a soft neck-worn collar and sent via Bluetooth to a cell phone which stores the data. This data is processed and reported to the user or uploaded to the cloud and/or to a local PC. With this system we are able to monitor people’s sleep continuously in a non-invasive and low cost method while at the same time collect a large database for sleep data which may benefit future advances in new findings and possibly enable a diagnosis of other diseases. We show as one of the applications of our system the possible detection of obstructive sleep apnea which is a common sleep disorder.

I. INTRODUCTION

Sleep is clinically linked to several serious conditions including diabetes, obesity and a number of heart diseases [9, 10]. Furthermore, sleep data such as from the respiratory system can be indicators of worsening in diseases such as Chronic Obstructive Pulmonary Disease (COPD). It is also true that OSA in diabetes patients can be a severe complication [13]. Despite this, gathering sleep data and tracking an individual’s sleep has been mostly limited to sleep labs with high costs for limited time or hospitals for some severe cases.

In addition researchers have found correlations between sleep data and several diseases such as asthma, Alzheimer’s disease, Chronic Heart Failure (CHF) and COPD [14-16]. These findings have been possible through expensive tests and monitoring. Being able to monitor an individual’s sleep continuously and at low-cost in a non-invasive method would benefit future advances in new findings and possibly enable earlier diagnosis of candidates of diseases. This would also enable knowledge on how lifestyle and environmental factors can affect sleep and sleeping disorders.

In this work, we have developed a non-invasive platform for monitoring vital signs throughout sleep. Our method is a

multi-signal technique for monitoring sleep in which a set of physiological sensors are incorporated inside a soft neck-cuff and are recorded continuously. This information is then analyzed for detecting known sleep disorders and also stored to build a large database for further investigations such as data mining to establish a wellness baseline and possibly diagnosing other diseases. Data transmission is wireless via Bluetooth to either a Bluetooth enabled cell phone or a nearby desktop machine for ease and comfort to the wearer.

We have implemented the above-mentioned system and have tested it on a common sleep disorder: Obstructive Sleep Apnea (OSA). Currently 4% of the male and 2% of the female adult population in the United States suffer from sleep apnea [2]. People suffering from OSA have episodes of blocked breathing during sleep despite respiratory efforts. OSA is characterized by periods of interrupted breathing and reduced breathing (apnea and hypopnea). Each apnea event can last from seconds to minutes [3]. These pauses in breathing must last at least 10 seconds to be considered an apnea event. Apnea events may occur 5 to 30 times an hour.

Individuals with sleep apnea are more prone to heart attacks and strokes relative to others. Symptoms of sleep apnea include depression, learning and memory difficulties, fatigue, poor concentration and daytime sleepiness. Untreated obstructive sleep apnea may lead to high blood pressure, cardiovascular diseases such as heart failure, stroke and heart arrhythmias. Therefore diagnosis of this disorder is critical.

The gold standard method for diagnosis of obstructive sleep apnea is overnight polysomnography (PSG) where the patient stays in a sleep laboratory while multiple sensors are attached to them. Many physiologic variables such as brain electrical activity, leg muscle movement, respiratory effort, airflow, heart rhythm, eye movement, oxygen saturation, etc. are monitored and recorded. This whole process is complex, time-consuming, costly and relatively invasive.

With the above mentioned neck-cuff we perform an early analysis of the sleep data to identify possible OSA candidates according to accepted standards. The system will provide a summary of possible apnea events detected and quantify the severity of sleep apnea and from that make recommendations if more accurate diagnosis is needed.

The remainder of this paper is organized as follows: Section II presents a study of related work attempting to provide a solution for sleep monitoring. Section III describes the system design and architecture in detail. It also demonstrates our visualization system. Later in Section IV

the data analysis and detection method used is elaborated. Finally we present our experimental results in Section V and conclude our work together with a description of future work in Section VI.

II. RELATED WORK

Recently a range of systems have been developed for monitoring physiological variables with applications for medical, assisted living and sports by the means of physiological sensors. There has been some work done in the sleep context. Harada et al. use a single sensor approach to monitor respiration and body movement using a pressure sensor sheet laid under the pillow [4]. Nishida and Hori, use a different approach by building a living space shaped system with multiple sensors in furniture to monitor respiration and by analyzing breath curve estimate oxygen desaturation frequency [5].

In [1] the authors use an acoustic method using only tracheal sound and SpO₂. They use a laptop to record and analyze the data connected to the sensors. [2] uses a single signal analysis only using blood oximetry data to detect sleep apnea.

Based on the mentioned related works in this area, our contributions in this work can be listed as: (a) development of a non-invasive multi-signal platform for sleep monitoring and pre-diagnosis of sleep apnea; (b) development of an automatic system which will collect, save and upload sleep data by the means of a Bluetooth enabled cell-phone, and (c) collecting a large set of sleep data for later investigation.

III. SYSTEM DESIGN

Below an overview of system architecture and the different sensing elements incorporated in the system are

provided. In part C we demonstrate the capabilities of our visualization system.

A. System Overview

Our platform is composed of several sensor nodes, a microprocessor and a Bluetooth transceiver arranged in a neck-cuff together with a cell phone or a desktop machine. The data from the cell phone or a laptop can be uploaded to a cloud, for data aggregation. This is depicted in Fig. 1. Fig. 2.a shows the neck-cuff system from outside- and against-user views and shows the different components of the system. These components are described in full detail in part B.

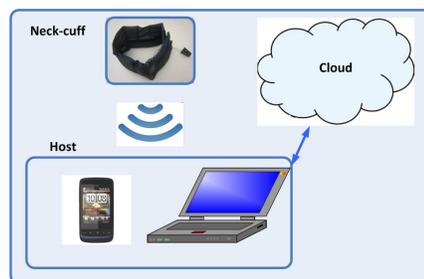


Figure 1. System Overview.

We use a low-power MSP430 microcontroller for collecting and pre-processing the data and transmitting it via a Bluetooth radio module. The operating voltage is 3.3v. The system is powered by a rechargeable 1000 mAh battery which allows the system to operate continuously for 9 hours. The Bluetooth module used in this design is the Roving Networks RN-41-SM.

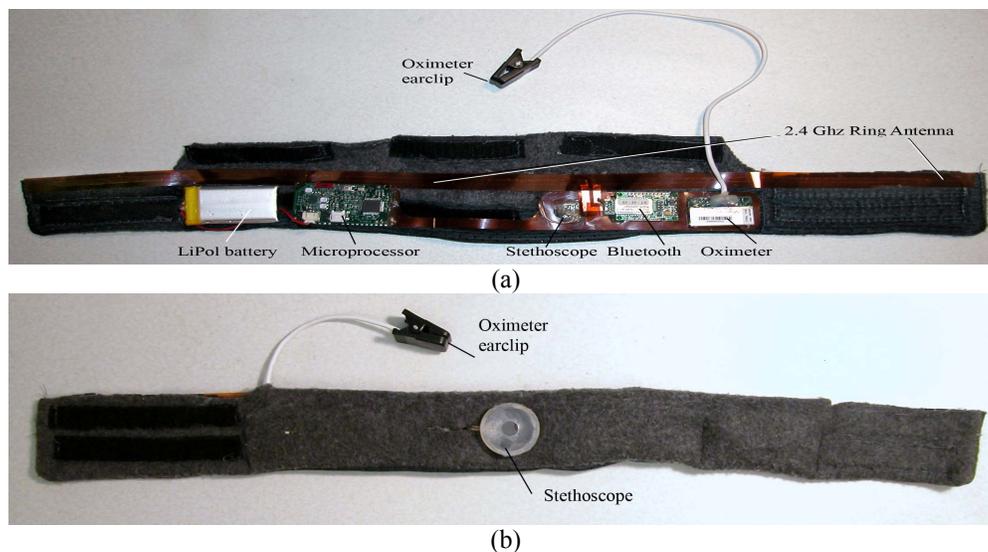


Figure 2. Neck-cuff (a) Outside-user view. (b) Against-user view.

B. System Components

Our sensing system is composed of the following components described in detail below. The arrangement of these components in the neck-cuff is shown in Fig. 2.a.

1) *Oximetry Sensor*: Pulse oximetry is a non-invasive method which allows monitoring of the oxygen saturation level of the blood. It is placed on a thin translucent part of the body, usually a fingertip or an earlobe. Red and infrared light is alternately passed from one side to the other. The processed ratio of absorption of the red to infrared light determines the SpO₂ value.

We use a pulse oximeter module model OEM III from Nonin [8] which takes continuous SpO₂ and pulse rate (BPM) measurements from a sensor connected to a Nonin 8000Q earlobe transducer. The OEM III module is a low power device that is integrated in our neck-cuff system. It sends a serial stream composed of SpO₂ and BPM to the microcontroller. The sampling rate for the pulse oximeter is 1 Hz. The Nonin Oximeter with 8000Q earlobe sensor is company certified to be accurate to +/- 4 digits in SpO₂ and +/- 3 BPM in pulse rate.

2) *Microphone*: We have integrated a small microphone with a large stethoscope-like diaphragm inside the neck-cuff which is placed against the neck and records breathing sounds. The data passes through an anti-aliasing filter at 1 KHz and the microcontroller samples this data at 2 KHz. The frequency of the optimal breath sounds we discovered is between 200 and 800 Hz. Frequency domain analysis is performed on the receiver side to capture this information and detect breathing. A low-power analog filter may be able to be used in future designs to lower the sample rate, record data size and power requirements.

Fig. 2. a shows the microphone which is visible from the back of the neck-cuff. This is done so that the microphone is placed with direct contact to the neck.

3) *Accelerometer*: Body movement can cause variation in the pulse oximetry readings [6,7]. Subjects go through many involuntarily movements throughout their sleep which affect the accuracy of the pulse oximetry readings and in turn the accuracy of our sleep analysis. With the use of an accelerometer we are able to detect most movements.

Other valuable information that can be extracted with the use of an accelerometer is the position of the head during each suspected OSA apnea event; whether the patient is lying on their back, left side or right side. The relationship between head position and apnea events is useful in the treatment of sleep apnea.

We use a tri-axial analog accelerometer from Analog Devices: ADXL327 in the neck-cuff. The sampling rate for accelerometer data is 1 Hz.

4) *Antenna*: To maintain continuous communication between the Bluetooth neck-cuff antenna and a cell phone antenna, the neck-cuff antenna needs to provide omnidirectional radiation. Even though positioned just a few

feet from the cell phone or PC, the antenna that is embedded on the Bluetooth module of the neck-cuff had many instances of lost connectivity throughout a sleeping event. This was due to the absorption of radiation from the lossy human neck depending on the orientation of the neck-cuff during sleeping. Therefore, an omnidirectional antenna which includes the neck will ensure the orientation of the individual sleeping will not have a major effect on the communication link. A suitable candidate is a circular loop antenna. Since the operation of the neck-cuff does not allow a continuous loop antenna to be implemented, a circular dipole antenna is utilized instead. The first iteration of this antenna was simulated, designed, and constructed by placing two copper strips along the length of the neck-cuff that are connected to the signal and ground terminals of the circuit. The antenna has a gap in the area where the Velcro is used to keep the neck-cuff around the neck. Fig. 3 shows an illustration of how the antenna performance was modeled using CST Microwave Studio, a 3D full-wave solver that solves for electromagnetic waves in the time domain. In this oversimplified model, the neck was modeled as a water body with a dielectric constant of 81. Since this antenna is a dipole instead of a circular loop, the radiation pattern will not exhibit complete omnidirectional characteristics. In addition, the neck, modeled as a lossy dielectric, contributes to the radiation pattern degradations as well. Nevertheless, this antenna implementation is better suited for this application than the smaller, factory installed antenna.

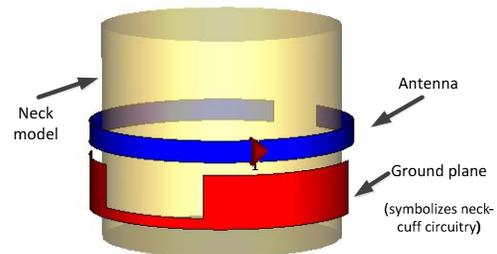


Figure 3. Illustration of antenna surrounding the neck model as modeled by a 3D full-wave simulator.

C. Visualization

The sensor data from the neck-cuff system can be streamed to a number of standard personal devices such as cell phones, PDAs, or laptop/desktop computers. Based on application needs, we have defined different views of the system.

1) *End-user View*: In the end-user view which is displayed on the individual's cell-phone, the user would be able to see the status of the neck-cuff, e.g. if it is connected correctly and information about signal integrity of the oximeter module. The user will be notified by a beep sound if the sensors are not collecting good data so that the neck-cuff can be repositioned. In addition, sensor data is displayed for real-time monitoring. Fig. 4 shows this view.



Figure 4. End-user view on a mobile phone

2) *Clinician View*: In the clinician view of the software, a clinician can access data of a specific sleep recording. Each sensor data is shown in its corresponding graph.

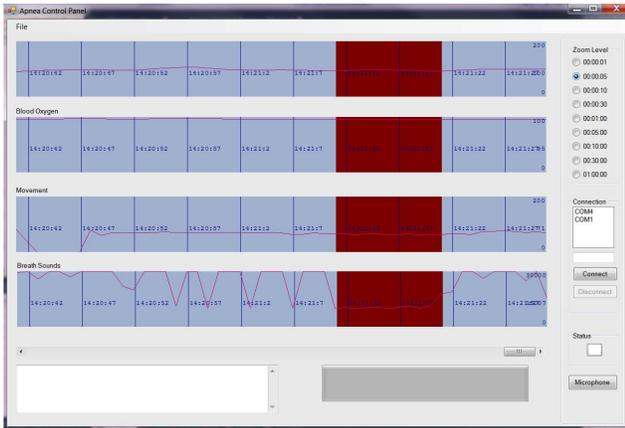


Figure 5. Clinician view

The clinician can zoom in/out to either view changes in a specific time/date or to view a whole night. Apnea/hypopnea events detected by our system are highlighted on the graphs depicted in Fig. 5.

A sleep summary together with AHI measures (an accepted apnea index), time of events and head positioning are also listed.

IV. DATA ANALYSIS

Apnea events are associated with drops of 4% or more in oxygen saturation level and at least 10 seconds of cessation of air flow to the lungs. One of the common methods for measuring the severity of sleep apnea is Apnea Hypopnea Index (AHI). It is calculated as the total number of episodes of apnea and hypopnea during sleep, divided by the hours of sleep.

As described in Section III, we use a multi-signal method for probable sleep apnea detection. Fig. 8 shows the steps of the data processing algorithm that detects events. Sound data is sampled at 2 KHz. This data is anti-aliased and sent to the

host side. Frequency of breathing is different among people but based on our experiments falls between frequencies 200-800 Hz. Fig 6 shows a spectrogram of breathing and non breathing of an individual.

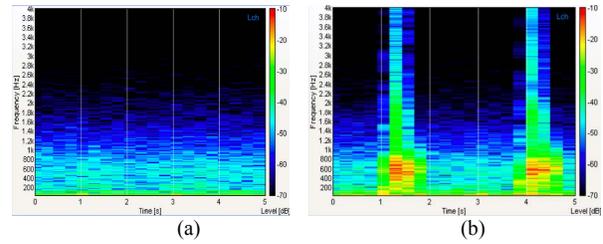


Figure 6. Spectrogram analysis on sound data. (a) No breathing. (b) Breathing at seconds 1 and 4.

Therefore, to obtain each individual's breathing frequency, we perform a calibration phase on the first two minutes of recorded breath data. In the calibration phase we perform frequency domain analysis to find breathing frequency and its energy level. We use this information to perform classification on the remaining sleep data. Sound data which has frequencies around the found breathing frequency with similar energy levels are classified as breathing. Higher energy levels indicate snoring or some vocalizing in sleep which is included in the sleep summary log.

Fig. 7 shows breathing and non breathing periods for two subjects collected through our system. This figure shows how signal energy level and dominant frequency is different among subjects and the role of the calibration phase.

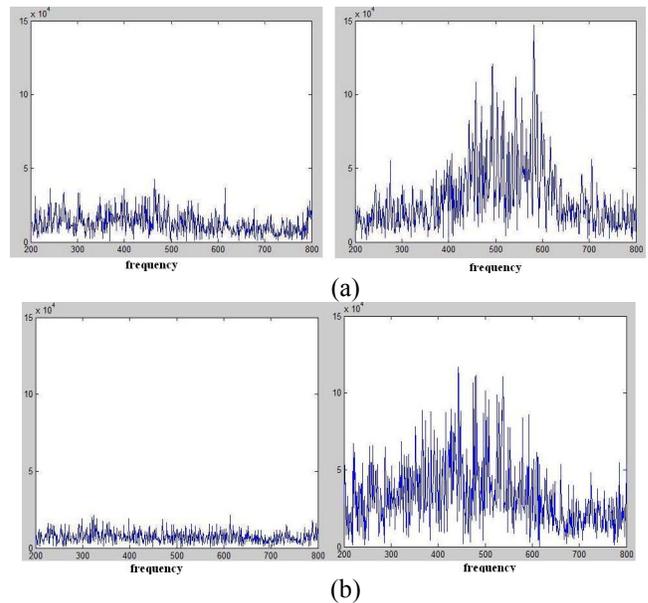


Figure 7. Frequency domain data of two subjects in non breathing and breathing states (a) Subject 1. (b) Subject 2.

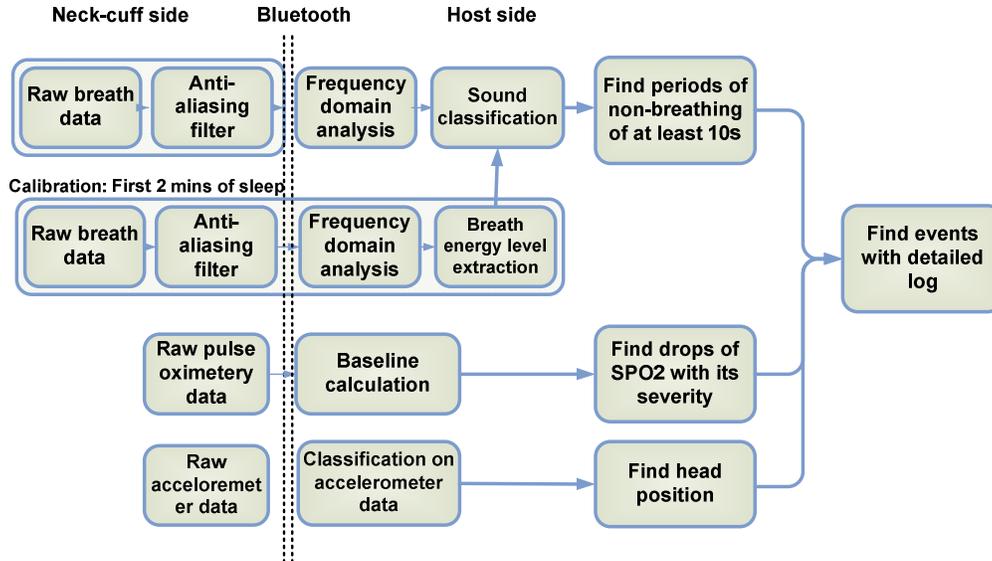


Figure 8. Signal processing algorithm

Different analysis is performed on SpO2 data to obtain apneas. A baseline for SpO2 data is evaluated. A baseline calculation is performed on a moving average window on the data. Any drop in SpO2 values below this baseline of a minimum of 4% are recorded together with the amount of drop and also the duration. These parameters determine the severity of apnea events. Fig. 9 shows a recorded drop in SpO2 readings of a subject.

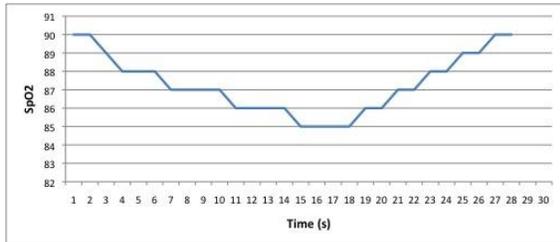


Figure 9. SpO2 drop during an OSA apnea event

By computing acceleration magnitude from a three axis accelerometer, head movements can be captured and head position can be determined. Head position is classified into three poses of left, supine and right. In the case of an event, head position is recorded in the log. Fig. 10 shows head positions of a subject through a session of data acquisition.

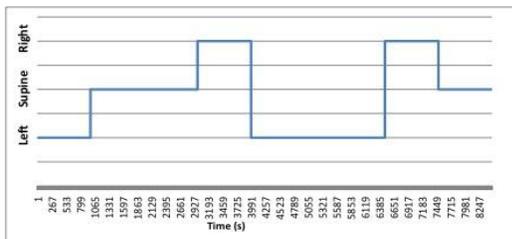


Figure 10. Head position classification using accelerometers.

In the next stage, all sensor data analysis is combined to determine events. Any changes in oximetry values that coincide with a movement are eliminated. This phase would remove most false positives in our detection mechanism. Then all drops of 4% or more in oxygen saturation level which coincide with non-breathing periods of at least 10 seconds are recorded as apnea events. An AHI index is calculated. Exact time of apnea event, duration, amount of drop in SpO2 and head position during the event of apnea is recorded in the summary.

V. EXPERIMENTAL RESULTS

An AHI index of 5-15 typically categorizes mild OSA; 15-30 indicates moderate OSA while AHI index of more than 30 is an indication of severe OSA. Three volunteer subjects wore the neck-cuff overnight at their homes for sleep monitoring. The result of the OSA evaluation together with AHI indexes is presented in Table I.

Subject	AHI	Apnea
1	23	Moderate OSA
2	2	No OSA
3	6.5	Mild OSA

In addition, subject 1 previously went through a full-night PSG study. The result of the full-night PSG also indicated moderate OSA with an AHI score of 29. This was the only system-wide ground truth we had access to in addition to the stated accuracies of the sensors. Table II shows part of the sleep summary of the system for subject 1. In the sleep summary, information on exact time of events is provided. Information such as amount of drop in SpO2

value, duration of non breathing event which is useful in determining the severity of events, is also provided.

TABLE II. PART OF SLEEP SUMMARY INFORMATION FOR SUBJECT 1

Event	Non-breathing period (s)	Amount of SpO2 drop (%)	Time of event	Body position
1	12	8	22:42:45	Supine
2	20	6	22:50:24	Left
3	12	7	22:52:35	Left
4	15	4	23:00:15	Left

VI. CONCLUSIONS AND FUTURE WORK

In this work we developed a non-invasive wearable neck-cuff system which is capable of performing real-time monitoring and visualization of sleep data. The system is composed of several physiological sensors integrated in a comfortable soft neck-cuff which is worn by the patient in their home during sleep. Sleep data is sent wirelessly via Bluetooth to a nearby cell phone for processing and storage. This data is useful for sleep disorder analysis, disease candidate selection and building a collection of sleep data used for further analysis and to establish a wellness baseline. We demonstrated the use of the neck-cuff system in the possible detection of obstructive sleep apnea. In the future we plan on producing a quantity of these devices and distributing to volunteers to collect a larger database and correlate against known clinical sleep disorder diagnoses.

The short battery life of the system is mainly due to the 2 KHz sampling rate. Since not enough is known about how to real-time process the breath sounds, the raw microphone data was Bluetooth communicated to the cell phone (or PC) for processing. In the future we expect to add a low power tunable analog band-pass filter to detect just breath sounds and thereby reduce the sampling to around a few Hz, lowering the Bluetooth duty cycle and drastically increasing the battery life.

Microsoft HealthVault [11] is a secure cloud-based platform for storing and maintaining health related information. Individual's access to HealthVault is through a secure account. A user can logon to their account from an application and update their information. In HealthVault, information concerning an individual is securely maintained via a *Record*. Health information together with personal information can be kept in a Record. In our system we would

like to gather sleep information from all individuals, diseased or not, using the neck-cuff. The application will ask the user for other health information which will be included with the sleep data at the end of the sleep period. Only an authorized researcher will have access to a large pool of sleep data for investigations.

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