NARCOLEPSY ASSISTIVE DEVICE

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Abstract – the endeavor of this research is to design and build a portable assistive device for narcolepsy patients to help them have more comfortable and productive life. A narcoleptic person suffers from a brain disorder that causes uncontrolled sleepiness. The device provides real time monitoring and assessment of the patient's sleep and alertness conditions round the clock.
An artificial intelligence algorithm is being developed to elicit objective data required to enhance patient evaluation and optimize administering medication. This paper outlines a system design for the narcolepsy assistive device hardware supported by marking the recent progress in the hardware design and testing processes besides to a brief description of the DSP algorithms employed.

Keywords: narcolepsy, assistive device, digital signal processor applications, brain waves

I. INTRODUCTION

Narcolepsy is a chronic neurological disorder of sleep regulation characterized by uncontrollable recurring episodes of daytime sleep and cataplexy. The episodes may last from few minutes up to a complete hour and is accompanied by intrusion of the dreaming state - known as the rapid eye movement sleep- into the waking state.
The exact cause of narcolepsy is currently unknown, but some theories and studies relate narcolepsy to the lack of hypocretin peptides in the brain which are neurotransmitters in the hypothalamus involved in regulating sleep.
An undiagnosed patient potentially will be subjected to the drawbacks of narcolepsy that will hinder the daily activities and normal flow of life. Referring to a survey carried by the UK narcolepsy patient association based to the Beck Depression Inventory (BDI), degrees of depression are common among narcolepsy patients [1]. This is an expected evolution to a series of social, educational, psychological, and financial difficulties experienced by narcoleptics [2] [3] [4] [5] [6].
So far, narcolepsy is not curable [7] and the proposed solution is considered a technological treatment for the narcolepsy patients in the form of a portable device for monitoring sleep and alertness states.

Research is in progress for designing and building a portable system for sleep monitoring and awareness assessment which is to be realized by developing artificial intelligence algorithms for digital signal processing as well as the required hardware which generally includes the electrodes, memory and the processing unit.
This device is remarkably different from vigilance monitoring systems [1] [7] [8] [9] in terms of the expanded tasks and capabilities.
The system is customized to be used by narcolepsy patients, thus the primary task is to assist narcolepsy patients through providing real-time monitoring of the electrophysiological signals; mainly the electroencephalogram (EEG) spectrum, and responding to the sleep and awareness states of the patient by issuing alerts in case of a potential narcolepsy attack, finally eliciting the objective data required by the treating physician.

II. NARCOLEPSY – A NEUROLOGICAL DISORDER

2.1 Narcolepsy effects:

Although a cure for narcolepsy is not yet available [7]; nevertheless, the behavioral and medical therapy can manage the symptoms and reduce their intensity and rate of occurrence. As a matter of fact, EDS and cataplexy (which are the main sources of disability) can both be controlled with drug treatment. Using central nervous system stimulants-amphetamines to control EDS has effective results, but side effects are inherent in pharmacological treatment and impose many undesired risks; for instance, amphetamines impose a potential risk of abuse.

A non-amphetamine drug was recently approved by the FDA for treating EDS; in the end, the patient is likely to develop tolerance to these types of medication [10].

2.2 Narcolepsy symptoms:

In brief, the key symptoms of narcolepsy are excessive daytime sleepiness, cataplexy, sleep paralysis and hypnagogic hallucinations [7] [11] [12] [13].
The following points explore the symptoms elaborately:

- **Excessive daytime sleepiness (EDS).** A state of involuntary sleepiness and extreme exhaustion which interferes with normal activities regardless of the sleeping habits. The EDS attack may be a microsleep lasting for few seconds or as long as an hour.
- **Cataplexy.** A sudden attack of muscle weakness and loss of muscle tone aroused by strong emotional response.
- **Sleep paralysis.** Momentary inability to move or speak while falling asleep or waking up which is similar to a cataplectic attack affecting the entire body.
- **Hypnagogic sleep paralysis.** Brief episodes of paralysis occurring when falling asleep.
- **Hypnopompic sleep paralysis.** Brief episodes of paralysis occurring when waking up.
- **Hypnagogic hallucinations.** Vivid hallucinations occurring at the onset of sleep.
- **Hypnopompic hallucinations.** Vivid hallucinations occurring when waking up.

III. ELECTROPHYSIOLOGICAL SIGNALS

Electroencephalography is the neurophysiologic exploration of the electrical activity of the brain by the application of electrodes to the scalp.
Active transport of ions through cell membranes results in bioelectric events that can be quantitatively detected in ionic voltages produced as a result of electrochemical activity of the cells known as biopotentials.

3.1 Electroencephalography (EEG):

Brain functions and activities can be extracted from the EEG signals which capture a spatio-temporal average of the brain synaptic activity of discrete radially orientated populations of the cerebral cortex directly underlying the measuring electrode [14] [15] [16].
Unlike the ECG (electrocardiograph), EEG recordings can't be directly associated with a single electrical phenomenon within the brain and this is due to the fact that the recordings represent a summation of electrical activities of a large number of individual neurons.
The reason EEG signals are being used is that they provide patterns that can be used to distinctively differentiate between different sleepiness and awareness states. For example, REM sleep which characterizes a narcolepsy attack is associated by EEG de-synchronization, muscle atonia and bursts of rapid eye movements [17]. While REM sleep is marked by activity of the head and neck muscles [Jacobson et al. (1964)]

3.2 Electrical properties of the EEG spectrum:

EEG signals are characterized by very low amplitude ranging between 10μV and 200μV peak-to-peak measured on the scalp using ordinary wet (gel) electrodes, whereas measured at the surface of the cerebrum they are about 10 times larger. This is due to the large skin impedance and increases the complexity of the bioamplifiers and electrodes used in EEG measurements. On the other hand, these signals are confined in a narrow spectrum starting from a fraction of a hertz and reaches 120 Hz. Having near DC frequency values and extremely low amplitudes, the signals are highly susceptible to noise, interference, artifacts and distortion.

3.3 Artifacts:

Artifacts are non-cerebral signals superimposed to the EEG spectrum and can be considered as internal noise generated within the human body and at the electrode-skin interface. Artifacts are different from external noise like EMI and 50/60 Hz mains interference. Usually artifacts have amplitudes comparable with the required EEG signals, thus they add to the complexity of computer-based EEG evaluation and analysis. Accordingly, they have to be detected and removed prior to processing the acquired EEG signals.

In an EEG acquisition system, the main sources of artifacts include skin stretch, electrode displacement, sweat and muscle motion

3.4 Electrooculography (EOG):

EOG monitors rapid eye motion (REM) by detecting dipolar current flow from the cornea to the retina which indicates the eye's angular displacement [15]. EOG is required for detecting the rapid eye motion REM sleep stages.

IV. SYSTEM ARCHITECTURE

Being a portable assistive device; the design has to abide by the guidelines and constraints for reliability, power consumption, weight, battery life, electromagnetic emissions and ease of use.

The device design involves two main phases:

1. Software layer: this includes the firmware and digital signal processing algorithms.
2. Hardware layer: this includes the electrodes and circuitry.

4.1 General review of the device tasks:

- **Data collection.** One of the roles of the device is gathering medical information about the patient’s state without intervention. This ensures that the physician will acquire precise data to improve diagnosis and administering the drugs.
- **EEG signal conditioning.** This step involves signal denoising and artifact removal which is crucial for computerized EEG signal analysis.
- **Sleep detection.** Sleepiness states are monitored in real-time by the DSP algorithms which in turn alerts the patient in case of a narcolepsy attack.
- **Data logging.** Uploads data to physician’s PC.
- **Trainability.** The sleep detection algorithms are adaptable to increase reliability and avoid issuing future false alarms. The algorithm has to adapt to each patient’s signal levels and patterns which are dependant on parameters such as gender and age.

4.2 Hardware layer:

Referring to figure 1, the system block diagram shows the signal flow from the scalp to the device

4.2.1 Electrodes. Electrodes are the sensors used to detect the vital signs and electrophysiological signals emitted by the body organs. The sources of EEG and biopotentials are ionic currents which are different from the electric current and can not be fed directly into electronic circuits, consequently; the electrode used in EEG detection is a transducer that converts the bioelectric potentials into an electrode potential proportional to the exchange of ions between the electrode surface and the electrolytes of the body.

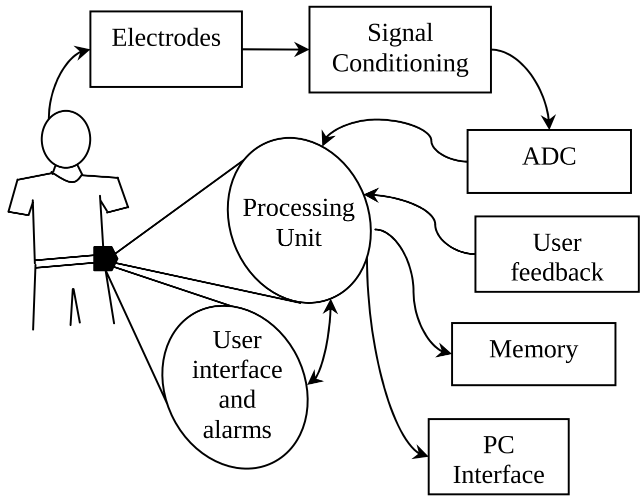

Figure 1 – System block diagram

The electrodes used in testing the performance of the device prototype are ordinary wet electrodes known also as gel electrodes. This category of electrodes suffers from a set of drawbacks which affect the EEG systems reliability, accuracy and portability. Applying wet electrodes involves many procedures and begins with skin preparation by abrasion which is required to remove the SC layer of dead cells to decrease the skin-electrode impedance to improve signal pick up. Then a conductive gel used to create a continuum of conductive layer for electric stability, the gel also is used adhere the electrode to the scalp for mechanical stability and decreases electrode motion artifacts. After applying the conductive gel, it is left to diffuse into the scalp. It is obvious that the process is time consuming and non-comfortable for the patient. Moreover, the wet electrodes can not be used in a portable device because cosmetically it is not

appropriate.
The device will use dry electrodes based on MEMS technology which in their simplest form resemble and array of high aspect ratio micro needles that penetrate into the epidermis layer of the scalp.
Prototypes of this category of electrodes proved to have outstanding performance in comparison with ordinary gel electrodes (Jacobson et al., 1964), [18] [19]. Referring to table 1, the comparison between the wet and dry electrodes surmise that dry electrodes are more convenient to use and will enhance the EEG monitoring system performance. Dry electrodes penetrate into the epidermis which is a layer of skin free from nerve cells and blood capillaries, thus the procedure is not painful and causes no bleeding. Electrically, signal pick is improved as the skin-electrode impedance decreases remarkably without the need for skin preparation. Mechanically, depending on the needles architecture, they can hold better to the scalp, which will diminish the electrode motion artifacts and increase the signal monitoring period. Besides, gel electrodes introduce electrode-electrolyte interface and electrolyte-skin interface while dry electrodes introduce only electrode-skin interface thus the noise and artifacts sources are less. The small size and the ease of use with no required skin preparation promote this type of electrodes to be used in EEG monitoring. Finally, being CMOS compatible, the micro-electrodes can be integrated with CMOS circuits in a monolithic structure.

Table 1 – Wet and dry electrodes

Wet electrodes	Dry electrodes
-Large size to satisfy electrical and mechanical constraints. -Require application of gel. -Require skin preparation (abrasion). -Long setup and cleaning time. -Introduce electrode motion artifacts.	-Do not require conducting gel. -Fast setup and cleaning time. -Improve mechanical contact. -Improve conductivity and signal pick up. -Diminish electrode motion artifacts. -Cosmetically concealable. -CMOS compatible.

4.2.2 Signal Conditioning. EEG signals detected have extremely low amplitudes (10µV to 200 µV) and require pre-amplification, filtering and amplification.

Pre-amplification and filtering. The detected EEG signal is pre-amplified at the source (electrode) with a small gain of 10 prior to relaying the signals to the main amplifier circuit at the device end. This is required to enhance the small signal immunity to noise and increase the signal-to-noise ratio (SNR) prior to further processing. This is followed by notch-filtering the 50/60 Hz mains interference and limiting the signal bandwidth.

4.2.3 Amplification. Instrumentation amplifiers are preferred as building blocks for bio-amplifiers because they can have high input impedance in the range of 1000MΩ with no degradation in the common mode rejection ratio (CMRR) which is a critical parameter in differential signal amplification. High input impedance is required to provide a strong voltage signal at the inputs of the amplifier. While high CMRR is required to reject interference and some electrode artifacts, for example due to electrochemical effects, the electrode-skin interface impose a DC offset of 1-2 volts.

Interference. The main events that can cause interference during bio-potential recordings are as follows:
1. The lead sway of the electrodes: displacement of the leads causes interference which affects the measurements and can be avoided by forcing the lead wires still during measurement.
2. Persons moving close to the subject: The interference induced by human movement results from static charges due to the existence of stray capacitance between the body and ground.
3. Bio-potential sources located within the body: For example of the interference from ECG signals and artifacts. This type of interference can be removed by adaptive filtering techniques.
4. Electromagnetic interference (EMI) from the other electromagnetic sources.

4.2.4 Analogue to digital conversion. The microcontroller used in the device prototype has a built-in multi-channel 10 bits successive approximation ADC. Experimental results showed that the built-in ADC performance sufficed the EEG monitoring system requirements and power consumption constraints. Currently, comparison between Nyquist rate ADCs, Microcontroller embedded ADCs and Sigma-Delta ADCs is being studied to optimize the system performance.

4.2.5 Processing unit. The processing unit is a combination of a commercial microcontroller and a digital signal processor connected in a master-slave architecture. This provides the low power interfaces and add-on circuitry of the microcontroller as well as the floating point capabilities of the digital signal processor. This makes it competent for the application. The microcontroller is the master of the device and manages all the hardware communications, watch-dog timers, A/D conversion, resource management and it can run in power saving modes. On the other hand, the digital signal processor is dedicated to executing the artificial intelligence algorithms and sending the results to the microcontroller. In the process of designing and customizing the processing unit, other available technologies were explored including PDAs which proved to lack the required processing power and capabilities.

4.2.6 Data Storage. Objective sleep assessment data is stored temporarily on the device until it is uploaded to the physician's computer. Flash memory modules are appropriate for the portable application due to the high capacity, small size and mechanical robustness.

4.2.7 User interface circuit. The user interface consists of an LCD module, keypad and alarms. The LCD module (figure 2) is for displaying the status of the patient, expert system advice, and device status besides providing auditory and sensory stimulation to wake a sleeping patient and alert companions in case of a narcolepsy attack.
This interface also allows the patient to feed back the device incase of erroneous sleep resolution to train the detection algorithm which require adaptation to the patient EEG waveforms.

Figure 2 – LCD capture of the user interface

4.2.8 PC interface circuit. The device updates the patient's profile on the physician's computer by logging the objective data via a PC docking port based on a serial link.

4.3 Software layer:
Figure 3 illustrates the software components of the device. The device firmware is the operating system that manages the device resources and controls signal and data flow. Besides, it provides a user interface though a LCD screen and a

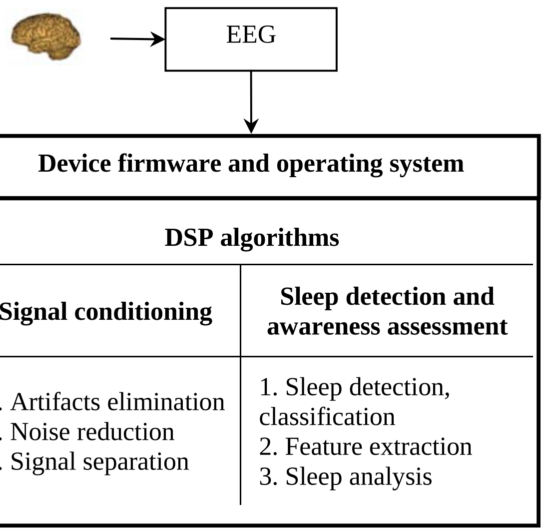

Figure 3 – Device software

customized keypad. Finally, it includes a serial link program to upload the objective data to the physician's computer.
On the other hand, the digital signal processing algorithms based on artificial intelligence techniques like Hidden Markov Model (HMM) analyze the captured EEG signals. The analysis and data extraction start with noise and artifacts elimination, signal separation then the processing proceeds with sleep detection and classification, and at last, data analysis and objective data generation.
The software includes an expert system layer which converts the detection and prediction results into practical advice required for enhancing medication administration. The expert system is based on the physician's knowledge and the patients' experience.

V. RESULTS

So far, all the experimental results are based on using ordinary gel electrodes which will be replaced by dry micro-needles electrodes which are in the early stages of design at the moment. Refereeing to table 1 and the previous section discussing the differences in performance between the wet and dry electrodes, it is anticipated to have an improved performance.
Currently, the device firmware is altered to distribute the processing between the device processing unit and a PC application that executes the DSP algorithms until the code is completely stable and optimized for code size to be downloaded to and executed on the DSP processor.
The input stage of the device has been modified and used for EEG monitoring and an application software was developed to read and display multi-channel EEG
signals on a PC. In addition, this was used to verify the performance and functionality of the system architecture. This had a numerical output

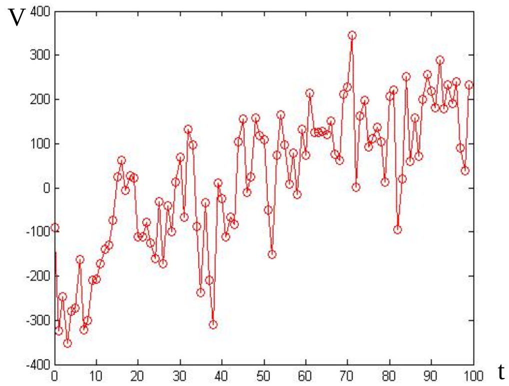

Figure 4 – Captured EEG signal

on the LCD display (figure 2) and a graphical output (figure 4) on the monitor. The experiment block diagram is shown in figure 5.

Additional applications:

The device can be employed in other medical applications as well. For example; the input stage of the device is an EEG acquisition system based on MEMS electrodes (microelectrodes) and can be used in portable and ambulatory EEG monitoring applications. Moreover; the device can provide vigilance assessment which is a matter of growing concern in road safety.

VI. CONCLUSION

A technological treatment for narcolepsy patients is proposed in the form of a portable assistive device. Besides to issuing alerts incase of a narcolepsy attack, the device runs a sleep detection, classification and analysis algorithm to provide objective data required for the treatment

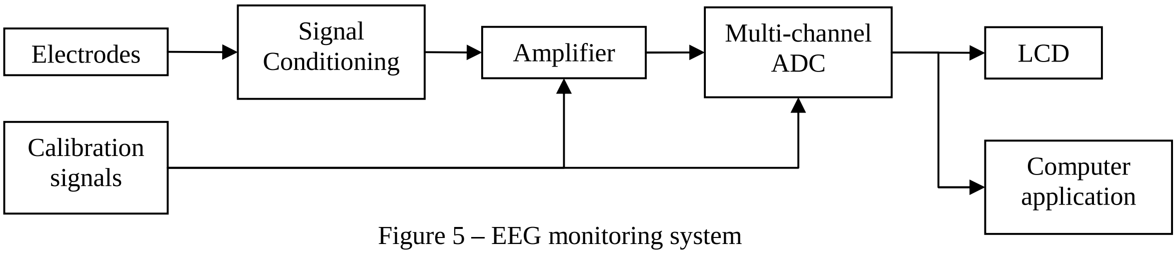

Figure 5 – EEG monitoring system

process.
The device architecture is outlined together with the recent progress and results.

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