

Ambulatory EEG NeuroMonitor platform for engagement studies of children with development delays

Ruhi Mahajan, Sergi Consul-Pacareu, Mohammad Abusaud, Md N. Sahadat, Bashir I. Morshed
Department of Electrical and Computer Engineering, University of Memphis, Memphis, TN USA

ABSTRACT

Engagement monitoring is crucial in many clinical and therapy applications such as early learning preschool classes for children with developmental delays including autism spectrum disorder (ASD), attention-deficit hyperactivity disorder (ADHD), or cerebral palsy; as it is challenging for the instructors to evaluate the individual responses of these children to determine the effectiveness of the teaching strategies due to the diverse and unique need of each child who might have difficulty in verbal or behavioral communication. This paper presents an ambulatory scalp electroencephalogram (EEG) NeuroMonitor platform to study brain engagement activities in natural settings. The developed platform is miniature (size: 2.2" x 0.8" x 0.36", weight: 41.8 gm with 800 mAh Li-ion battery and 3 snap leads) and low-power (active mode: 32 mA low power mode: under 5mA) with 2 channels (Fp1, Fp2) to record prefrontal cortex activities of the subject in natural settings while concealed within a headband. The signals from the electrodes are amplified with a low-power instrumentation amplifier; notch filtered ($f_c = 60\text{Hz}$), then band-passed by a 2nd-order Chebyshev-I low-pass filter cascaded with a 2nd-order low-pass ($f_c = 125\text{Hz}$). A PSoC ADC (16-bit, 256 sps) samples this filtered signal, and can either transmit it through a Class-2 Bluetooth transceiver to a remote station for real-time analysis or store it in a microSD card for offline processing. This platform is currently being evaluated to capture data in the classroom settings for engagement monitoring of children, aimed to study the effectiveness of various teaching strategies that will allow the development of personalized classroom curriculum for children with developmental delays.

Keywords: Autism Spectrum Disorder, Electroencephalography, Embedded system, Programmable System on Chip.

1. INTRODUCTION

The human brain consists of billions of neurons that process and transmits information through an electrochemical process. Noninvasive human scalp electroencephalogram (EEG) can monitor these oscillatory wave activities occurring inside the brain that relates to the mental states, stimulations and activities. EEG signals are typically classified as delta rhythm (0.1–3.5 Hz), theta rhythm (4–7.5 Hz), alpha rhythm (8–13 Hz), beta rhythm (14–30 Hz), and gamma rhythm (>30 Hz)¹. There is copious research in using EEG for neuroscience, cognitive science, cognitive psychology, and psychophysiological areas, and through large-scale studies, neuroscience experts have identified various regions of the brain (lobes) responsible for specific activities. For example, frontal lobe is more associated with problem solving, mental flexibility, judgment, creativity, foresightedness² and deficiencies typical for ASD whereas temporal lobe is primarily responsible for auditory sensation, perception, language comprehension, long-term memory and sexual behavior³.

Autism spectrum disorder (ASD) and attention-deficit hyperactivity disorder (ADHD) are increasingly becoming a significant medical challenge. A recent study from the Centers for Disease Control (CDC) in 2013 reports that 1 in 50 child suffers from ASD in USA, up from 1 in 80 child several years ago. It is critical for doctors and physiologists to have the ability to monitor, track and understand diagnosis, prognosis and treatment of such developmental delays to be able to combat this challenge. As a practical framework to encounter this challenge, we are studying EEG activities from prefrontal cortex of children (ages 1 to 3 years) with various types of developmental delays in a natural setting - a classroom at the Special Kids & Families (SKF), Memphis, TN- an early learning preschool.

Several multichannel (based on International 10-20 electrode placement) EEG systems are commercially available, for instance, 14 channel *EPOC*⁴ neuroheadset which connects wirelessly to PCs through USB dongle and can provide access to raw EEG data for about 12 hours of continuous use, *B-Alert X*⁵ a 4 channel EEG system with Bluetooth and SD card features. The first FDA-approved EEG device *iBrain*TM⁶ which is a single channel EEG recording tool has an electronic

box attached to an elastic head harness and electrodes that can be attached to the head during sleep. It has a rechargeable battery that provides hours of continuous recording and a USB port for data transfer.

Though commercial wireless EEG systems exist, none of the currently available devices are practical to be used in the natural settings to record brain activities of the children with development delays. Two primary practical obstacles are: (1) EEG recordings are to be taken from the children between the age of 1 to 3 years in the classroom, while none of the available device in the market allows us to take such measurement while the child is performing regular activities. The existing devices are large and uncomfortable to wear by children of 2-3 years of age; they are either harness or helmet based which kids might feel reluctant to wear for long time. (2) The commercial devices are visually identifiable and easily discernible; it leads to deviation or shift of cognitive activities among children, leading to erratic behavior atypical to regular activities.

With this prospective, we have developed an ambulatory EEG NeuroMonitor Platform. This paper presents the methodology of designing a miniature two channel, wireless EEG data acquisition system that can record the prefrontal lobe activities of the subject under study. The developed EEG system can be concealed within a headband so that a child can wear it comfortably in natural settings for long duration. Since it is difficult for these children to communicate with the instructors effectively to evaluate the responses to classroom activities, the designed NeuroMonitor aims to aid the process by providing an additional modality of measure through EEG activities from the prefrontal cortex to the instructors, therapists, psychologists, and neurologists in evaluating the engagement of children while being instructed by monitoring corresponding brain regions.

2. HARDWARE DESCRIPTION

Research has shown that the engagement activities are very prominent in the frontal lobe areas⁷. The customized 2-channel EEG device is thus primarily focused to capture the brain activities at left prefrontal area, FP1 and right prefrontal area, FP2 (electrodes locations as specified by the International 10–20 system⁸). The first phase of the project was to develop the hardware for data acquisition. In due process, we have developed two versions of NeuroMonitor platform (mentioned herein as the first prototype and the second prototype). The hardware of the designed NeuroMonitor is broadly divided into two main stages: Analog front end for signal conditioning and Digital back end for signal acquisition and processing. The key hardware aspects of this platform are discussed in the sections below.

2.1 Analog front end

A typical adult human EEG signal is about 10 μV to 100 μV in amplitude when measured from the scalp⁹. So, it is required to amplify the signals before any further processing. For amplification, each electrode (GS26 Pre-gelled disposable sensor, Bio-medical Instruments) is connected to one channel of the instrumentation amplifier and a common system reference electrode is connected to the other input of that channel (one channel of amplifier per pair of electrodes). The location of the reference electrode is on the left mastoid, where no electrical brain activity is expected. The low power instrumentation amplifier (ISL28270, Intersil Americas LLC) amplifies the voltage between the active electrode and the reference typically 26.5 times at a high CMRR of 110 dB. This gain in the instrument amplifier is set by two external resistors, the feedback resistor R_f , and the gain resistor R_g . The output of the instrument amplifier is calculated by equation (1) given below:

$$V_{out} = \left(1 + \frac{R_f}{R_g} \right) V_{in} + V_{ref} \quad (1)$$

where V_{in} is the potential difference across two inputs of the channel, V_{out} is the output voltage of that channel and V_{ref} is the reference voltage.

2.2 Filtering Stage

The local power system's frequency might couple significant 60 Hz noise to the EEG signal. So, the amplified EEG signals from both electrodes are filtered for 60 Hz noise using active notch filters. After that, signals from each electrode are passed through an active 2nd-order low-pass Chebyshev-I filter cascaded with a passive 2nd-order low pass filter, which is designed to remove high frequencies for anti-aliasing purposes and implemented using the on-chip operational

amplifiers (internal to the PSoC). The cut off frequency is set to be 125 Hz and the gain offered by this filtering stage is 1.61. The graph of the frequency response i.e. magnitude and phase response for the overall design is given in Figure 1. The last stage of filtering includes high pass filter with a cut off frequency of 0.5 Hz for each electrode to avoid saturation due to DC offset, before further amplification. The filtered signals are then amplified with operational amplifiers of the PSoC with a gain of 16.5. The overall gain of the front end is calculated to be 703. This resulted in a stable analog front-end, which is less susceptible to baseline wandering typical to biopotential.

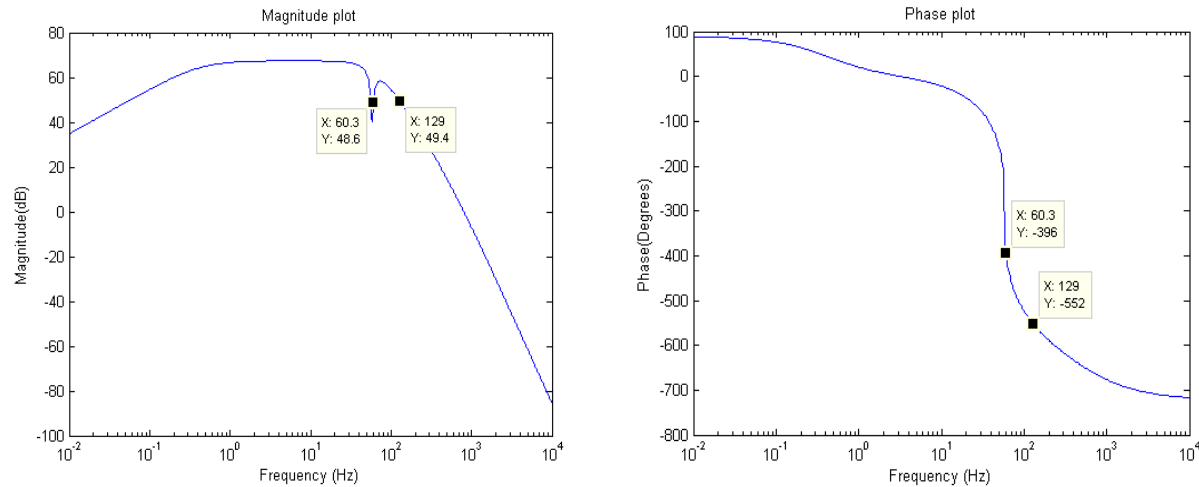


Figure 1. Magnitude and phase response of the analog front end.

2.3 Digital back end

The core of the design is the Programmable System-on-Chip (PSoC 3 CY8C38, Cypress Semiconductor) embedded microcontroller with unique array of reconfigurable analog and digital blocks. It integrates a microcontroller unit (MCU), 64 KB of flash and 2 KB of RAM, configurable analog (op-amp, Register, Capacitor) and digital (ADC, DAC, digital filters, UART, USB, SD card controller) peripheral functions on a single chip. This low power chip with a feature to go in shut down mode will help to reduce the overall power consumption and also in reducing the number of components onboard board since the Operational Amplifiers of the chip are utilized. In this design, all op-amps of the chip are utilized for power and footprint optimization. As the amplified and filtered signal needs to be digitized before being wirelessly transmitted or stored on the microSD-card, the digitization is achieved via a 16-bit analog-to-digital (ADC) converter within the PSoC at the sampling frequency of 256 sps. The digitized signal is collected in real-time with two FIFO (first in first out) buffers acquiring data in tandem, while data can be sent wirelessly or stored in the onboard microSD card. To temporarily hold the sampled data every 3.9 ms for two channels, the size of the buffers was set to 256 bytes requiring 0.25 seconds to fill up. Interrupts are triggered when a buffer is filled, that stored the buffer data to the microSD card (along with wireless transmission in online mode) while the other buffer is being filled. The complete block diagram of the designed NeuroMonitor is given in Figure 2.

2.4 Bluetooth Transceiver

We have used a Bluetooth transceiver for initial synchronization and wireless data transfer in online mode. The rationale to select RN-42 (Roving Networks) for wireless transmission was its low power consumption and small footprint. This Class 2 Bluetooth module with inbuilt antenna consumes typically 12 mA when in sniff mode for 100 ms and 45 mA when connected with data transfer for 5 ms (when there is no data to transmit), or as long as it takes to transmit data if data is available for transmission. Running in the 2.4 GHz ISM band, this Bluetooth device can cover range up to 20 meters, which suits our application. The baud rate for transmission is set to be 115,200 bps.

2.5 Peripheral Components

The NeuroMonitor has its ability to work in real-time i.e. in online mode in which the captured EEG signals are wirelessly transmitted to a remote device; and in offline mode in which the EEG signals are saved in the onboard memory in the microSD card. This allows design of a reconfigurable, adaptive and robust system, where the brain

activities can be continuously recorded in an unstructured practical scenario. The designed device also has a USB plug-in provision for charging and data transferring. The battery level of the device can be checked through a pin of the PSoC, and can be used for notification for recharging when the battery is below certain threshold. To charge the Li-ion battery

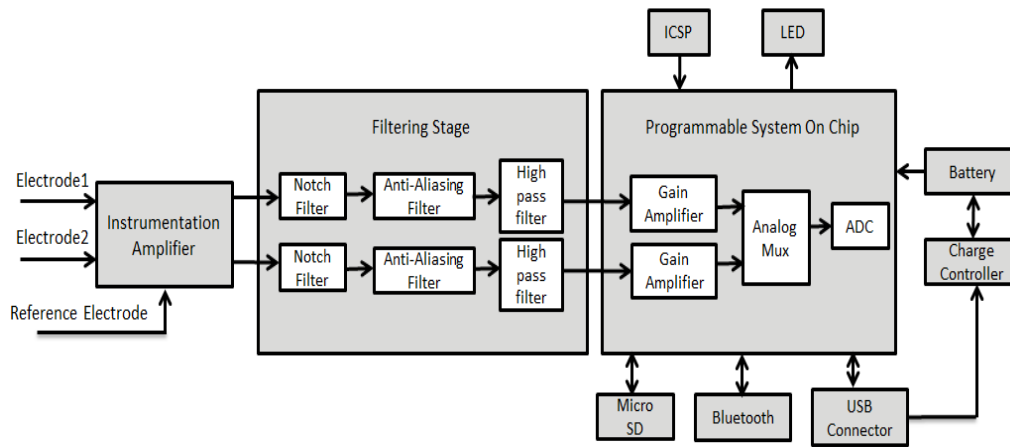


Figure 2. Functional Block diagram of the ambulatory EEG NeuroMonitor platform.

(with over current and over-discharge protection), the user can either connect the microUSB port with a personal computer or a wall charger. To ensure that the battery is not overcharged (as Li-ion battery might get permanently damaged), the charging is controlled by the linear charge management controller (MCP73831, Microchip Technology, AZ, USA). The board has the capability to continuously collecting EEG data from the two channels for approximately 10 hours with an 800 mAh capacity battery.

3. SOFTWARE IMPLEMENTATION

The software development for the user interface and programming the microcontroller unit were also iterated. The graphical user interface (GUI) was created using Visual Basic.Net (version 2010, Microsoft Corp., WA, USA) and it provides the user the ability to interact with the board. User can select operating modes: Online (recorded EEG signals will be sent wirelessly to a remote device where the software is installed), or Offline (EEG signals will be saved on the onboard microSD card). The selection allows flexibility to the user to choose depending on the nature of the application requirement. User can also change the sampling rate (if required, maximum up to 8 x 256 sps, limited by software not hardware) and sampling duration (if the data collection to be stopped after certain period, not currently incorporated) of the configurable delta-sigma ADC of the PSoC from the selection menu of the interface. Before starting the signal acquisition, if required, user may also keep the record of details like *Subject ID*, *Researcher ID*, *Experiment start time*, *Experiment ID*, *EEG Device ID*, *File name*, *Notes* etc. on the GUI panel. This parametric information will be saved as the header information of the file on the microSD card (for offline mode) or on the file on the remote computer (for online mode). Figure 3 shows the snapshot of the prototyped GUI. *Plot* and *Reading data* buttons on the panel are additional utility features by which the user can convert the binary data into integer format, and plot the EEG data without any other analysis tool.

The central unit of the designed data acquisition system is the PSoC 3 (microcontroller unit integrated with many peripherals), which is programmed using its designer software PSoC Creator. The Integrated Design Environment (IDE) of the PSoC's designer software is used to customize the interconnect using its library of analog components like 16-bit ADC, 8-bit digital to analog (DAC) converter, Operational amplifiers, UART, USB and emFile component (it provides an interface to the SD cards formatted with the FAT file system) and program the MCU. Similarly, digital components of designer software's library like LEDs and timers are customized in the design leveraging the dynamically generated API libraries of code¹⁰.

In the software flow, initially PSoC waits until the time is synchronized (Desktop program sends the time to the MCU, and the MCU sends it back to the desktop program, and if the difference between the sent and received time is less than one second the synchronization is successful, else it will iterate until error or success). Then, PSoC checks for the user input (given through GUI) about the mode: online or offline mode. If user has selected *Online* mode, the Bluetooth module remains on the sniff mode for data transmission throughout the data acquisition process, but if *Offline* mode is selected, Bluetooth is turned off once the board is synchronized with the remote device. To optimize the power consumption, Bluetooth works in the sniff mode, where it sleeps for 100 ms, then wakes up for 5 ms to check if there is any data in the input port for transmission. If it finds any data, it transmits the data to the remote computer. In either case, it returns to sleep mode and continue the sniffing operation.

Potentially the NeuroMonitor can also be programmed to change the sampling factor (options of x1 or x2 or x4 or x8, over the base sampling rate of 256 sps) set by the user. The results presented in this paper are for the single-ended 16-bit delta-sigma ADC of PSoC configured for the sampling rate of 1x256 sps. To save the sampled data from each channel, MCU is interrupted every 3.9 ms using the timer interrupts. In the interrupt service routine (ISR), two buffers – Array 1 and Array 2, each of size 256 bytes is used to save the sampled EEG data from the ADC. On the first interrupt, Array 1 starts receiving the data and if this array is filled, the MCU is interrupted, while the Array 2 starts receiving the data. In between the two interrupts, data is sent to the microSD card (if offline mode is selected) or to the remote device wirelessly (if online mode is selected). The buffer size was selected based on tradeoff between memory requirement and time required for each buffer to fill. The two buffers only occupy 0.5 KB of RAM ($\frac{1}{4}$ of available resources) while able to store data for a duration of 0.25 s with the selected sampling rate, which provides sufficient time to allow writing of one complete buffer content into the microSD card, or transmit wirelessly (115.2 kbps). Two flags have been used to ensure mutual exclusiveness of the buffers to avoid data corruption from the two ADC channels. The functionality of the NeuroMonitor is described in terms of the StateChart diagram given in Figure 4.

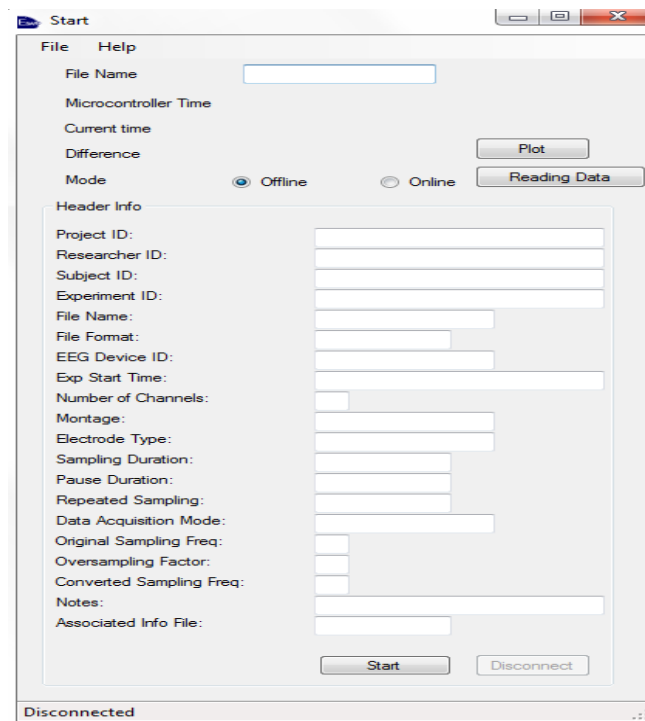


Figure 3. Front panel of GUI for user interaction.

4. RESULTS

After series of experiments done with the known sinusoidal input to verify the performance of the board, EEG data has been collected with the two electrodes arrangement on the prefrontal cortex at FP1 and FP2 lobe locations. The reference location as discussed before is the left mastoid (bone of left ear). On the analog front side, the signal was tested after the

filtering stage and before the ADC of the PSoC with the oscilloscope. The gain of the front end was measured by applying a micro-volt AC sine wave signals (10 Hz) at the input and measuring the corresponding output, which yielded a front end gain of 775 (10% error). This could be due to our inability to measure the micro-volt input supply reliably in a noise free environment. Further testing with high-end equipment is planned. For EEG data collection, the offline mode was selected from the GUI, where the amplified, notch and band-pass filtered sampled data from both channels are saved on the microSD card.

The protocol used for EEG data collection was as follows. During the data acquisition process, the subject was asked to frown, then blink eyes four times, and then frown several times. After 75 seconds, the subject was asked to relax for 1 minute. During the relaxing stage, subject was advised not to blink. After that period, the subject is again asked to blink eyes few times and frown continued to the end of the recording. The recorded data was about 200 seconds with the Male subject. The captured data has been analyzed with the analysis tools Matlab (Mathworks Inc., MA, USA) and EEGLAB. The channel outputs were observed to be coupled with some 60 Hz interferences, so zero phase infinite impulse response (IIR) notch filter was designed and applied in Matlab to attenuate this noise. The signals are plotted after cubic spline interpolation. The recorded EEG signal from the designed NeuroMonitor for channel location at FP1 is shown in Figure 5, and the corresponding power spectral density for the frequency analysis is plotted in Figure 6.

The plot of recorded cortical activity for the first 7 seconds has been magnified to annotate epochs of the blinks and frowning movement more clearly is Figure 7. To detect the event-related spectral perturbation (ERSP), time-frequency spectrum for the segmented EEG data is also plotted using EEGLAB (Figure 8). The frowning activities and the four eye blinks occurrence at ~ 2 sec, 3.3 sec, 4.5 sec and 6.5 sec, are quite significant in terms of the intensity changes in the spectral content of the data. It has been observed that the measurement is slightly affected by the baseline wandering which, however, can be removed by using filtering algorithms in Matlab or EEGLAB.

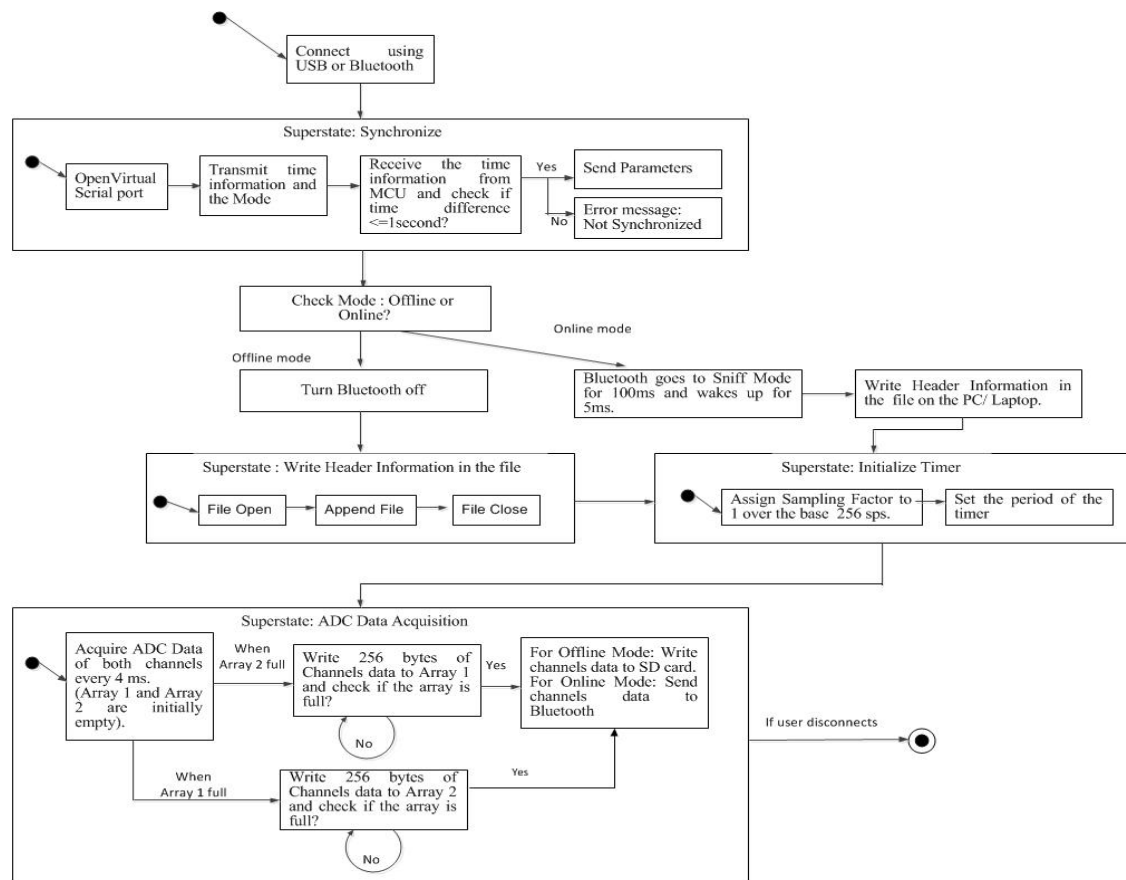


Figure 4. StateChart diagram of the ambulatory EEG NeuroMonitor platform.

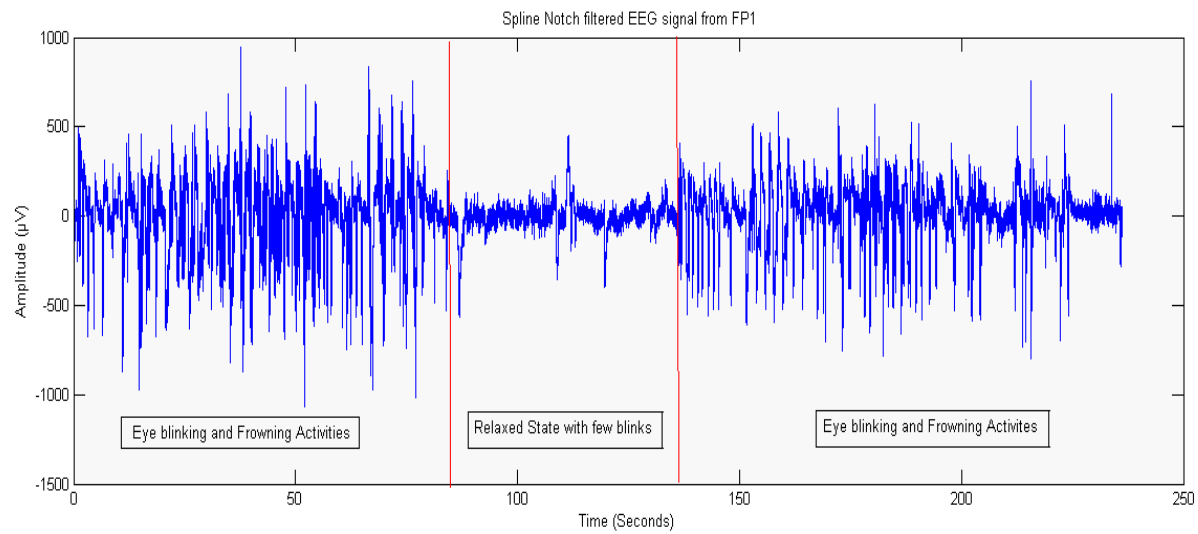


Figure 5. Spline notch filtered EEG signal from FP1 (Red vertical lines represent the regions in cortical activity for different states).

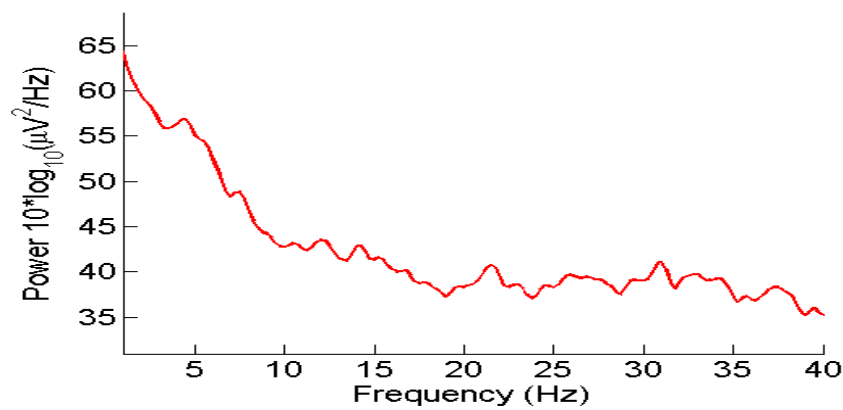


Figure 6. Power spectral density of the brain signals collected from prefrontal lobe location FP1.

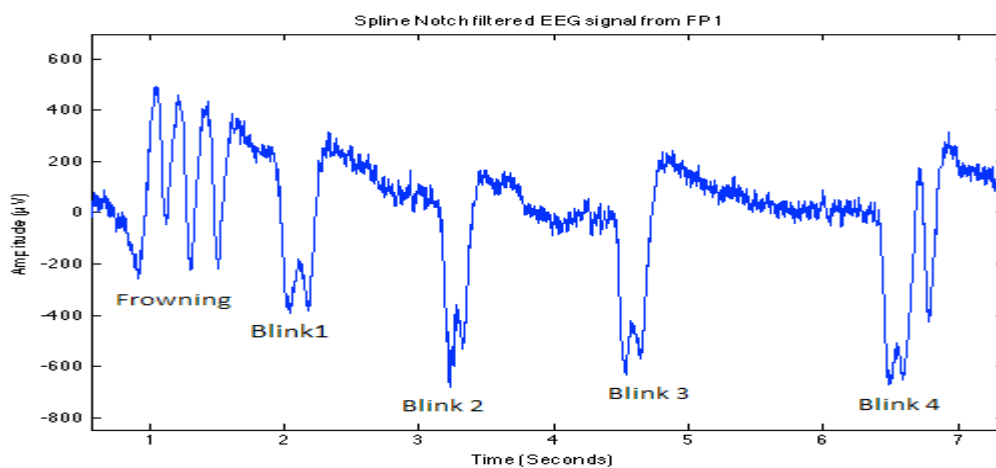


Figure 7. Segmented EEG data from FP1 for the first 7 seconds represents one frowning and four eye blink events.

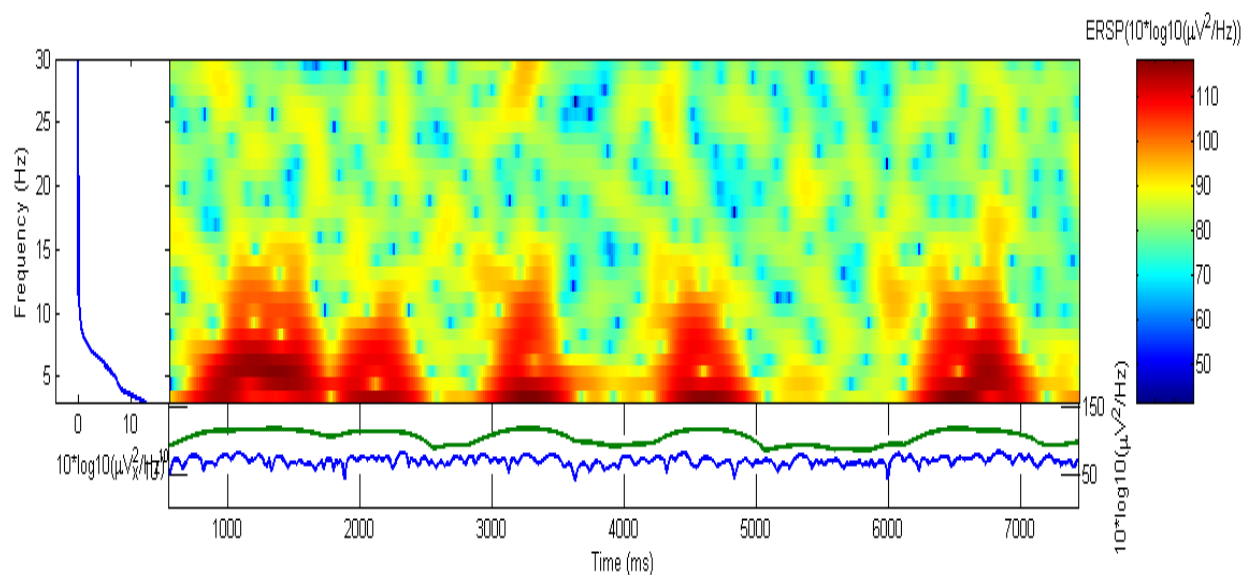


Figure 8. Time-frequency spectrum for the first 7 seconds EEG data (corresponding to Figure 7).

The current prototype of the NeuroMonitor can collect EEG data from subjects in practical settings in either online or offline mode, to provide a flexible and reconfigurable platform of biometric data collection. The first prototype development of hardware was larger due to debugging hardware, while the second prototype has been optimized for footprint. Photographs of the two prototyped versions of EEG NeuroMonitor are shown in Figure 9. This developed EEG NeuroMonitor system is being deployed for the engagement monitoring study of six children with development delays by recording their prefrontal cortex brain responses at SKF during May to December 2013.



Figure 9. (a) First prototype of the ambulatory EEG NeuroMonitor device inside a cap. (b) Second prototype NeuroMonitor device with smaller footprint can be concealed within a child-sized headband.

5. DISCUSSIONS

In comparison to the commercially available single channel EEG systems like EPOC, MindWave¹¹ etc. and research use EEG systems designed by different research groups, i.e. Zhu et al.¹², Lin et al.¹³, Gneccchi et al.¹⁴, Lin et al.¹⁵, Brown et al.¹⁶, and Matthews et al.¹⁷, some of the key features of the designed ambulatory EEG system are tabulated in Table 1.

Table 1. Key feature comparison table of the developed EEG NeuroMonitor device with commercial and other comparable EEG devices.

Features	EPOC ⁴	MindWave ¹¹	Lin ¹⁵	Brown ¹⁶	Matthews ¹⁷	NeuroMonitor (This Work)
Microcontroller	-	-	ARM925	MSP430 F1611	DAQ microprocessor	PSoC 3
ADC resolution/ sampling rate	12 bits/-	12 bits/-	16 bits/500 down-sampled to 250 sps	11 bits/500 or 1k sps	-/240 sps	16 bits/256 to 2048 sps
Weight	~150 gm	90 gm	-	-	170 gm including enclosure	41.8 gm (with 800 mAh Li-ion battery and 3 snap leads), 64 gm including headband)
Dimension	16 Sensor Arms with the longest arm of length ~ 5".	Sensor Arm up: 8.8" x 6.1" x 3.6". Sensor Arm down: 8.8" x 6.1" x 6.4".	PCB size: ~ 6 x 5 cm. Three stacked layers.	-	PCB size: 3.25" x 2.25"	PCB board dimension: 2.2" x 0.8" x 0.36"
USB Charging	USB charging	No	No	-	-	MicroUSB charging
SD card	No	No	No	No	No	2 GB Memory (microSD)
Wireless transmission	Proprietary wireless, 2.4 GHz Band	Bluetooth Class 2	RF3100/3105	2.4 GHz (Nordic nRF24L01)	GFSK (2.4 /2.525 GHz) ISM	Bluetooth Class 2
Hardware Filter range	0.2-45 Hz	3Hz – 100Hz	0.5 to 100 Hz with 60 Hz notch filter	0.5 to 128/210/375 Hz	1 to 30 Hz	0.5 to 125 Hz (Notch filtered at 60 Hz)
Battery run time	12 hours	6-8 hours	-	30 hours	80 hours	Up to 10 hours

Legends: "-": unknown, "sps": samples per second, "DAQ": data acquisition

6. CONCLUSIONS

This paper presents the NeuroMonitor platform designed to provide scalp EEG data from two channels. The device is miniature with Bluetooth wireless connectivity along with on-board storage capability, and can be completely concealed within wearable accessories, such as headband, cap, or visor. The device is miniature, lightweight (41.8 gm with 800 mAh battery and 3 snap leads) with two channels for scalp EEG data capture from the prefrontal cortex (Fp1, Fp2 of Intl. 10-20 system). The platform is miniature with dimension of 2.2" x 0.8" x 0.36", while weighs only 64 gm with enclosure (headband). In low-power active mode, it consumes 32 mA when active and under 5mA when low power mode. The EEG signal is band passed with 0.5 to 125 Hz with 60 Hz notch, and sampled with 16-bit ADC at 256 sps. The PSoC based system offers flexibility of storing the data in onboard microSD card, or transmitting in real time with Bluetooth

wireless module. This developed EEG NeuroMonitor device is practically deployable in real-life settings to allow the subject to perform routine daily activities without any distraction that could result in deviation or shift from regular activities. Current study to monitor engagement of children with developmental delays is expected to lead towards identifying individual characteristics of each child with unique developmental delays, and would allow the development of personalized instruction plans which might be better suited for individual needs and promote positive cognitive growth trajectories.

ACKNOWLEDGEMENTS

The authors would like to thank Julie Grower and Stephanie Phillips, Executive Director, Special Kids & Families (SKF), Memphis, TN, for collaborating in this project. This work is supported in part by Strengthening Communities Initiative (SCI) Capacity Building grant, 2012.

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