WEEGEE: Wireless 8-Channel EEG Recording Device

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Abstract— **Electroencephalography (EEG) is the recording of electrical activity on the scalp. Typical EEG instruments which perform such recordings are expensive, elaborated and bulky. It is, therefore, important to design a low-cost and portable brainwave recording device. The objective of this investigation is to design an 8-channel EEG system with integrated hardware and software interface. The device takes advantages of a new system on a chip (SoC) to reduce circuitry component requirements and keep the cost low while maintaining functions of advanced instruments such as lead-off detection. It communicates with a host computer via Bluetooth. The mainboard is powered by a powerful ARM Cortex microcontroller capable of processing a large amount of live stream brainwave data. Real-time view of 8-channel EEG data is presented in the software interface after passing through typical EEG signal filters to filter out environmental noise and drifting current. A variety of applications can be developed based on this new device such as low cost Brain Computer Interface (BCI), ambulatory assistive device or a quick assessment tool for brain damage on the field. We have tested simple BCI tasks as well as sensing mental states using this system.**

Keywords— **Wearable EEG, BCI, sensory circuit, ADS1299.**

I. INTRODUCTION

An EEG recording device gauges electrical activity at the scalp surface. The majority of these signals are produced by the summation of potentials from a large number of neurons within the brain. A typical EEG recording system includes essential functional modules such as the signal acquisition block, signal processing block, and an interface for users to interact. Each component has its own challenges in the pursuit of low-noise EEG. Low noise, high common-mode rejection ratio (CMRR) analog to digital converter (ADC) is a key element to make the acquisition block. On the other hand, the signal processing block needs both robust algorithms to filter out noises and processing module to keep up with high data rate from multiples recording channels. A standard clinical EEG device has at least 16 different channels [1].The graphical user interface software doesn't face many technical challenges as the two previous modules, but it requires careful design to support smooth interactions with the hardware.

Brainwaves range from 0.5uV to 100uV in amplitude. They have been categorized into 4 basic groups depending on the frequency. Delta waves have frequencies less than 4Hz. Delta waves dominate during dreamless sleep. From waves from 4 Hz to 8Hz, they are called Theta waves. Alpha waves have frequencies from 8 to 12 Hz. They dominate when eyes are closed, and the brain is in a relaxed state. The rest called Beta waves are signals with frequencies greater than 13 Hz. Beta waves associated with alertness and active attention [2]. By identifying the frequency of current dominant waves, researchers were able to recognize the current arousal state [3].

EEG has a wide range of applications from clinic to game entertainment. Some critical clinical applications are monitoring alertness, coma and brain death; locating areas of damage following head injury, stroke; investigating epilepsy and locate seizure. Additionally, other interesting applications are evoked potentials and brain-computer interface (BCI). Evoked potentials are used in marketing research and detecting lies. BCI are used to create a game controller in-game entertainment [4].

Advancements in electronic have enabled smaller, better and lower cost EEG recording device in recent years. Some wearable EEG recording prototypes were successfully developed such as a wireless non-contact cardiac and neural monitoring system [5], a helmet to monitor physiological signal[6], a portable device for real-time drowsiness detection[7]. This study presents a recording hardware which fits for these applications. Moreover, the proposed design is smaller and, it performs better than the previous model.

The new design in this paper is built around the low noise, low power, and high CMRR TI ADS1299 chip. The new chip provides a compact design which meets EEG recording device criteria. It enables wearable EEG recording devices to be built with much less complexity and much better performance. The chip integrates essential modules for EEG acquisition together inside it. For previous studies, modules are built separately and integrate together on the printed circuit board (PCB). Those approaches introduce outside noise interference which is bad for the recording system.

In this paper, the overall system architecture is presented first as the guidance for rest sections. It includes design methods, major design considerations, data flow and how the hardware interacts with software. Next, analog system design is discussed. This section deliberated how EEG signal from the scalp surface is transferred to the ADC. Subsequently, digital system design is explained. It's about how analog signal is converted to digital data, how the system process, transfer data and display them in the human machine interface in MATLAB. Last parts are system verification with BCI application and conclusion.

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II. SYSTEM ARCHITECTURE

A. Overall system architecture

All circuit components are packed into a circuit board which is smaller than a regular smartphone size. Users can comfortably carry the device in a pouch holster all day long for monitoring activities if required. It consists an Arm Cortex M4 STM32F4 as the main microcontroller and the ADS1299 for Analog to Digital Converter (ADC) tasks. A 3.7V/1000mAh lithium polymer battery powers the whole system which draws approximately 30mA at steady state. This battery will last for 24 hours after fully charged. A power management system is also included to charge the battery. Constant system voltage is maintained regardless input voltage from the battery by a buck/boost converter. The device communicates with a computer or a smartphone via Bluetooth or Serial interface. Real-time graphs of all channels are presented on the PC.

This system uses standard gold cup wet electrodes to acquire data. It has a clear advantage in term of signal quality compares to dry electrode. This electrode terminal was made by a 0.1' female header compare to a standard DIN Touch Proof Connector to save space on the Printed Circuit Board (PCB).

B. Analog system design

The device takes continuous 8 channels 24bit ADC EEG signal from non-invasive electrodes. The gain at the Programmable Gain Amplifier (PGA) is 24. It's the maximum PGA of the ADS1299. The ADC module used a bipolar power supply at -2.5V and +2.5V. This bias electrode (or right leg electrode) is the virtual ground of these two supplies. The second option for this bias electrode is a signal from the internal bias amplifier. This bias op-amp sums input data from all channel and compares the sum with a reference voltage to generate the bias signal. The sample sampling rate is 250 sample/second. Even though the ADS1299 module is capable of sampling up to 16k samples/second, 250s/s is sufficient for BCI application whereas brainwave frequency is below 50 Hz. It's well below the Nyquist frequency 125Hz. On the other hand, the data throughput of the system is limited by the serial port protocol. The reliability of data transfer drops when the baud rate is increased.

Digital signals are sent from the ADS module to the microcontroller for preprocessing via SPI interface. Whenever a new data package is ready to transfer, the ADS1299 module will signal the microcontroller via the Data ready pin. Multiple ADS1299 devices may share one SPI line. They are synchronized by the START pin of every device.

Two electrode input options are provided in the current design. The first option is the single ended input which is the typical design of EEG recording device. All negative pins of eight channels are wired internally to a single pin SRB1 of the ADS1299. Therefore, these configurations are able changed by firmware commands. The second option is differential input. Every channel has independent positive and negative input. This configuration provides better noise reduction effect in BCI application based on our experience.

Table 1 Overall WEEGEE system specification [8]

Item	Value
Number of channels	8 (expandable to 32)
Analog Input Option	Differential and single ended input for all channels
Resolution	24 bit
Min input voltage step	22.3nV
Input voltage full scale	188mV
CMRR	-110db
Analog power supply	Dual ±2.5V
System power supply	Single Lithium polymer battery cell 3.7V
Steady state current	30mA

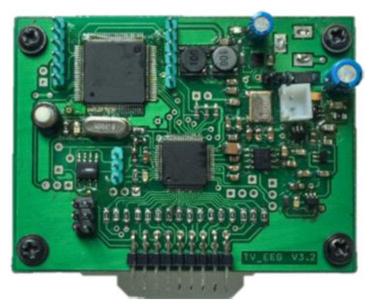

Fig. 1 Actual WEEGEE system circuit board

C. Digital system

According to Figure 2, the peripheral controller of the STM32F4 takes recording data from the ADS via SPI interface. The data package consists of 3 status byte information and 24 EEG data bytes. The microcontroller converts these two complement values to decimal and repackages them. The counter is added to these packages as a rudimentary way to monitor data integrity. A checksum or other techniques may be implemented to improve this process.

After processing the data, the STM32F407 chip sends data in packages to the computer via serial/Bluetooth for real-time display and data recording. Users may access these data via Bluetooth on a smartphone or an RS-232 serial port. This is system is performing at 380400 baud rate with a reliable output. We transferred 150kb during a test without dropping any byte. During our investigation to use Bluetooth Low Energy

(BLE) for the design, we find out that this protocol data transfer rate is slow, and the package size is limited to 20 bytes or less. It opposed to high data transfer rate of EEG recording devices whereas multiple channel information is recorded simultaneously. In the next stage, data will be processed within the STM32F407 chip on the device. It will compute FFT to support Steady State Evoked Potential (SSVEP) BCI. It will be possible to use BLE to send status data to a smartphone or computer.

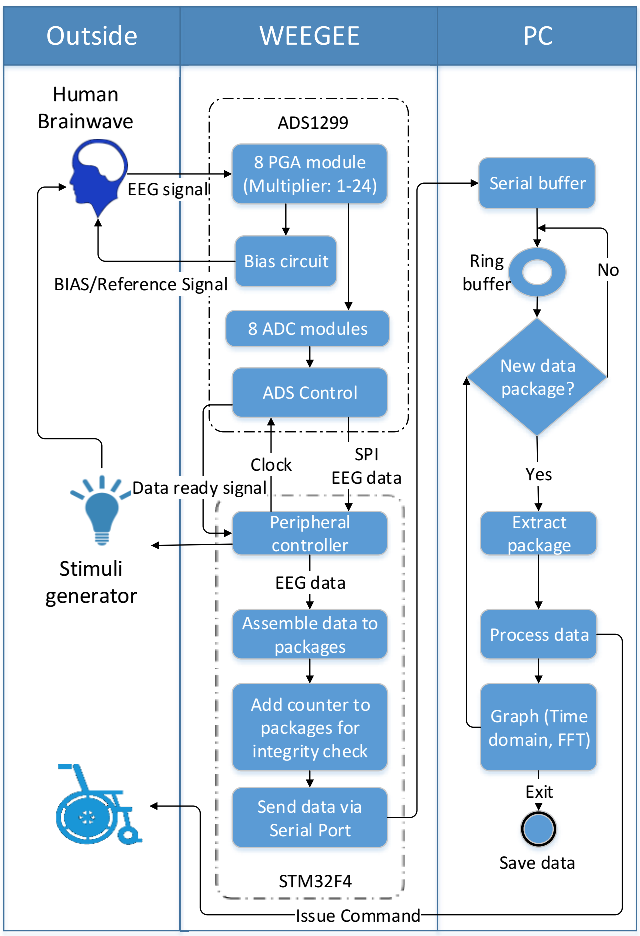

Fig. 2 Overall system architecture

D. Man-machine interface

The interface is built on Matlab. Even though Matlab may not be the best tool to handle large real-time data, we found it's powerful with much ready-to-use signal processing toolboxes. This is a key factor for EEG data analysis. Data from the STM32F4 is transferred to PC serial buffer periodically. MATLAB put these data chunks to a Ring Buffer. This is a key component in this design to balance the transfer rate for serial data and the processing time of previous packages. In our previous design, we faced intermittent package drop because PC's serial buffer was full and MATLAB hasn't finished the current process to take more data. Increasing the buffer size alleviated the problem; however, a large buffer introduced a long delay between signal acquisition and presentation.

Whenever a new set of packages is available in the ring buffer, the program extracts them to channel level data and plot it on the interface. A rolling plot presents last 1000 sample (4 seconds) values. These values are filtered by a DC blocker to eliminate drift current and a low-pass filter at 45 Hz to eliminate electric hump and indifferent signal. Real-time FFT is also present for SSVEP BCI tasks. The program also checks the counter of every incoming package to monitor the data integrity. Data of every channel is saved for offline analysis after each recording session.

III. SYSTEM VERIFICATION AND BCI PARADIGM

The system performance is validated with two well-known experiments. These trials provide obvious EEG signals which are confirmed by other researchers.

A. Detect alpha waves

This experiment concentrates on the analysis of the alpha rhythms (in the range of 8-12 Hz). Alpha brain waves boost up in EEG signal when subject's eyes are closed, and when subject's eyes open, alpha waves' amplitude reduce. This is an ordinary feature of EEG data processing. From the standpoint of a hardware designer, it's an important assessment for EEG recording hardware to verify that the system can measure ultra low brainwave signal.

The subject is a student (23-year-old) who participated voluntarily in this experiment. The experiment comprises two phases. First, the subject sits and relaxes on a chair with his eyes open for 15s. There are none stimuli in front of the subject's eyes. Second, the subject closes his eyes in 5s and opens his eye in 5s for every trial. This protocol is illustrated in Fig 3. Every run consists at least 5 trials. We conduct 5 runs in the session. EEG data is recorded in two differential channels. Gelled electrodes are placed on the subject's scalp according to the International Electrode (10-20) Placement System. One Ground (bias) electrode is placed on the left mastoid. The differential pair of channel 1 is placed on the O2 and the right mastoid. The differential pair of channel 2 is placed on the Oz and O1. The sampling rate is 250 Hz. EEG data was high-pass filtered at 0.3Hz to avoid DC drift and a low-pass filter at 43Hz because the signal of interest would be around 8-12Hz. Data is analyzed and visualized using a Matlab Graphical User Interface (GUI). The Power Spectrum Density (PSD) graph of one run is presented in Fig. 4. The result coherences with the hypothesis in which PSD of alpha waves is high (in red color) when subject's eye is close; PSD of alpha waves is low when subject's eye is open and relax.

Eye open 15s	Eyes close 5s	Eyes open 5s	Eyes close 5s	Eyes open 5s	...	Eyes close 5s	Eyes open 5s

Fig. 3 Protocol for detecting alpha waves

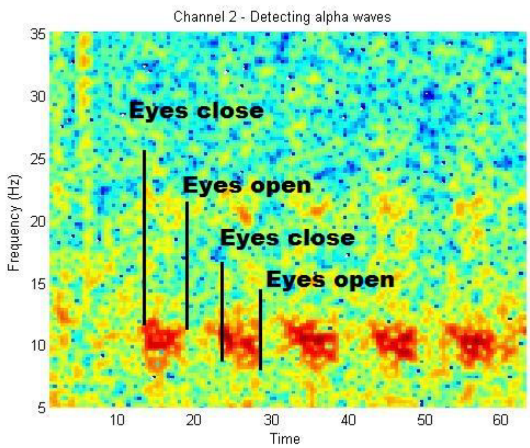

Fig. 4 PSD graph to detect alpha waves

B. SSVEP Task

This experiment is set up based on the SSVEP phenomena. When a stimulus (i.e. flickering screen) is presented to the subject at a certain frequency. His brains wave will boost up at this frequency significantly. In this experiment, the subject is another student (26-year-old). The subject sits on a chair and stares at the LCD screen. The flickering screen will alternate between stimuli (showing flickering at 12.5Hz) for 4s and non-stimuli (showing black screen) for 4s. We record 4 trial in a run. Electrodes placements and filters setting are the same as the previous experiment.

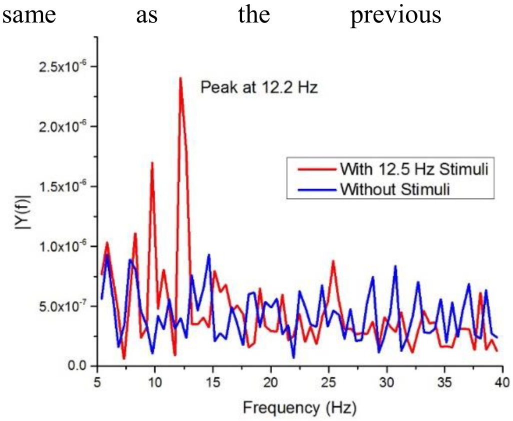

Fig. 5 Single-Sided Amplitude Spectrum of EEG signal

Figure 5 is the FFT plot of 2 seconds recording data with stimuli and without stimuli. The primary peak of the FFT is at 12.2 Hz is significant which is near to the 12.5Hz target. The Matlab GUI will detect whether a stimulus is present or not base on the peak frequency value and the signal to noise ratio at this peak. We successfully demonstrate the stimuli detection algorithm and illustrate it on the GUI.

IV. CONCLUSIONS

This paper explains the design of a wireless low-cost EEG recording device. The spec of this device is close to a standard clinical device [1]. A working prototype is presented. It's capable of replacing traditional clunky EEG recording device to perform some BCI applications. This device may also be used for prolonging EEG monitoring task. It can run for a day with a single battery. Further work needs to be done to make it as a stand-alone device without attaching to a computer. A derivative device could be used to monitor and alert epilepsy seizer. In the near future, we plan to build a low-cost sleep study device for developing country. Extensive field tests and certifications are main obstructions toward this goal.

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