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Wireless and Wearable Auditory EEG Acquisition Hardware Using Around-The-Ear cEEGrid Electrodes

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***Abstract*— Aside from a clinical interest in electroencephalography (EEG) measurements of real-time data with a high temporal resolution, there is a demand for acquisition systems that are operable outside the laboratory environment. In this study, we designed a wearable and low-power EEG system for multichannel EEG acquisition beyond the lab doors. Around-the-ear cEEGrid electrodes are used to capture 8 biopotential channels which are amplified by low-power precision instrumentation amplifiers and passed on to an analog-to-digital converter (ADC). An ESP32 microcontroller captures the data from the ADC and stores it on an external SD card. The proposed system is compared to a state-of-the-art EEG acquisition system (BioSemi) to assess its diagnostic power for auditory brainstem responses (ABRs). The recordings with our portable system match, and even outperform, the baseline method's specifications. Our hardware opens up new avenues for fast sampling-rate auditory EEG recordings that can be used in hearing diagnostics, damage prevention and treatment follow up.**

***Index Terms*—EEG, cEEGrid, around-the-ear EEG, ADS1299, ESP32, Auditory Brainstem Response, Biopotentials**

I. Introduction

Electroencephalography (EEG) has been omnipresent in clinical research (e.g. epilepsy diagnosis [2], assessment of functional brainstem disorders [3]). Although no considerable changes in the way of EEG recording have occurred since the first documented EEG experiments [1], everything has changed in terms of EEG acquisition systems. Recent years have seen a significant shift towards acquisition methods that are smaller and cheaper than the well-known clinical methods used in hospital and labs [4]. Emerging brain-computer interface (BCI) technologies offer an advantage compared to conventional methods since these are low-cost, have a convenient operation and are non-invasive [5]. However, conventional EEG signal acquisition, by means of professional equipment, are in general not flexible nor portable enough to be incorporated in these BCIs. Hence new acquisition methods have been developed to achieve a convenient and stable system performance on low cost hardware with the versatility of monitoring in non-hospital environments. These wearable systems are mainly battery-powered, resulting in an immediate limiting factor that is the battery life. However, there are also technical limitations (i.e. modest signal resolution, small bandwidths and lower sampling frequencies) that should be taken into account.

In the hearing technology field, EEG measurements are applied for the screening of the hearing pathway of a patient as well as for research purposes (i.e. tinnitus [6], speech-in-noise perception [7]). In these studies, the Auditory Brainstem Response (ABR), a type of auditory evoked potential recorded to a series of acoustic transients, can be seen as a crucial biomarker. To capture the dominant ABR wave peaks occurring 1-7 ms after the stimulation click however, a minimum sampling frequency of 6kHz is required [8], rendering the present wearable EEG solutions [9], [10] (with sampling rates up to 1 kHz or lower) insufficient for this purpose. Solving this methodological constraint for portable EEG systems can be seen as instrumental in search of EEG solutions deployable in the auditory field.

In this work, a hardware system is introduced that has a high sampling frequency (16kHz) while maintaining a high acquisition performance for around-the-ear electrode channels. The proposed system is low-power, portable, robust and has a reduced noise floor compared to a state-of-the-art system. The system allows for wireless data transmission and data storage, allowing to capture complex patterns of auditory stimulation in real-time, which provides a high application potential for future auditory EEG applications.

II. System Design

The design of our system can be divided into 4 physical components (Fig. 1) corresponding to the steps followed in the data acquisition: The commercial cEEGrid sensor electrodes (A) capture the biopotentials omitted by the brain, these signals are amplified differentially by the preamplifier (B) before being transmitted to the motherboard (C) that contains the supply circuits, filter circuit and the analog-to-digital converter (ADC) that sends out the digital signals to the microcontroller (D) for storage. The whole system is battery powered with 2 6000mAh lithium-polymer batteries, which allows for 3 hours of continuous measurements. The designs of the electronic circuits are made in KiCad, the communication protocols are written in C++ and Python.

A. cEEGrid-electrodes

Because our system focuses on auditory EEG responses, we work with cEEGrid-electrodes developed by the group of Bleichner and Debener [11]. These non-obtrusive electrodes can provide 24-hr robust signal quality [12] and, compared to a conventional cap EEG, are less intrusive, improving

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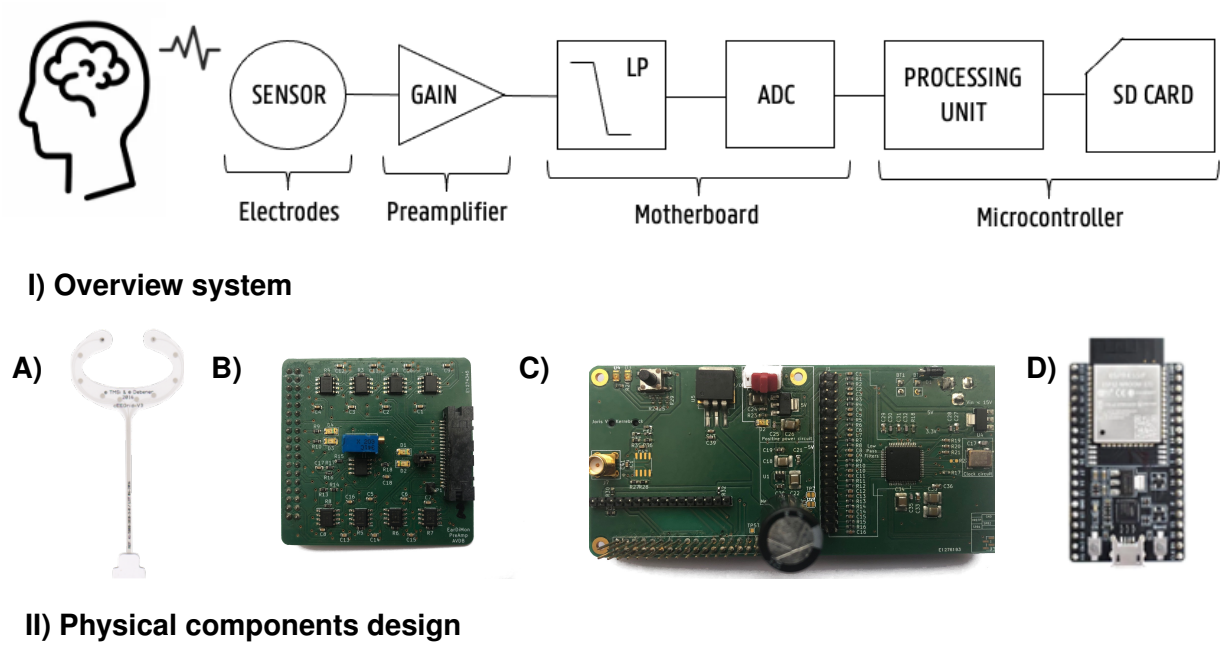

Fig. 1. **System design:** I) Functional block diagram giving an overview of all components in the designed system. II) Physical appearance of the 4 principal components of the design: A) cEEGrid electrode B) Preamplifier circuit C) Motherboard D) ESP32 microcontroller.

portability. The main drawback compared to clinical systems is the lower number of electrode channels (32 or 64 for cap EEG compared to 8 here). However, since the application of this system is focused on hearing diagnostics, these 8 channels positioned around the ear should suffice to collect ABRs, as shown in [13].

B. Preamplifier

The amplitude of a human EEG signal is in the order of 10μV to 100μV, however, the sub-cortical auditory responses of interest here are considerably smaller (0.2μV [13]). Hence, we chose a preamplification gain of factor 100, based on the input range of the ADC converter. We used low-noise ($7nV/\sqrt{Hz}$) INA828 operational amplifiers for each of the 8 channels, with a common mode rejection ratio (CMRR) of -110dB and an offset voltage of 0.5μV. To decrease the common-mode input voltage, we used a driven-right-leg (DRL) circuit, which holds the head at a steady voltage near ground level and reduces the influence of the other biopotentials generated by the body (i.e. noise).

C. Motherboard

The motherboard is fed by 7.4V lithium batteries and is supplied in the correct range through voltage regulators. The output signals of the preamp are passed through a set of low-pass, anti-aliasing filters to support the behaviour of the ADS1299 chip [14], which is the focal point of the system. This eight-channel, low-noise, 24-bit, simultaneous-sampling delta-sigma ($\Delta\Sigma$) analog-to-digital converter, was designed to be used in medical instrumentation studies, which also includes EEG measurements, due to its low power consumption and low cost. Here, the eight analog input channels are operated with a pseudo-differential input mode while we opted for the highest programmable sampling rate of 16kHz and a gain of 1 since the (low-noise) amplifiers of the preamp allowed for better signal-to-noise ratios compared to the internal amplifiers of the ADS1299. The motherboard is also equipped with a trigger circuit, important for the collection of ABR measurements, as well as an external oscillator. Samples of 27 bytes are returned by the ADS1299, of which the first 3 bytes contain the 24 status bits. These are followed by the final 24 bytes, holding the information of the 8 input channels (24-bit resolution).

D. Microcontroller

The microcontroller used in this project, the ESP32-WROOM-32 [15] chip from the Espressif Company, is a multi-purposed, two processor core, low-energy consuming MCU with on-board memory. A double buffer technique is used on this controller that stores the data in the reading buffer after data intake via serial peripheral interface (SPI) from the ADS1299. Simultaneously, the writing process passes on the content of the previous buffer cycle, stored in the writing buffer to an SD card via the 1-bit SD protocol, where all the EEG data is stored and can be handled.

III. Evaluation

To assess the performance of the proposed system, a comparison is made to a state-of-the-art research EEG measurement system. We performed a standard measurement on a test subject and derived the specifications of our proposed design.

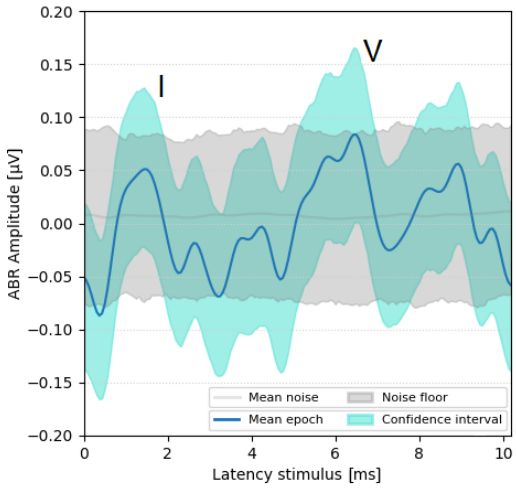

Fig. 2. **Measured ABR signal:** Average ABR response in response to a 80μs click with a peak-equivalent sound-pressure level of 100dB measured with our portable system. The, averaged over 3000 samples, time domain signal is plotted in blue, together with a 95%-confidence interval. The statistical noise floor is indicated in grey (α = 0.05) together with the mean value of the noise (grey line). The channel that is plotted for each subject is the fourth cEEGrid channel, referenced to the eighth channel [13]. Wave-I and Wave-V are annotated on the plot and their latency corresponds to the expected latencies for a 100dB peSPL click [18].

A. BioSemi reference system

For reference measurements, the ActiveTwo Mk2 BioSemi is used [16]; it is a common go-to wired system for the acquisition of biopotentials in a stationary laboratory set-up. This 64 channel, 24-bit resolution device operates with Active-electrodes (sintered Ag-AgCl electrodes) and was set for acquisition with a high sampling rate (16384 Hz).

B. Auditory Brainstem Response (ABR) test protocol

We performed measurements following the procedures outlined in [13]. The subject was seated in a reclining chair in a double-walled, electrically shielded listening booth. The cEEGrid-electrodes were positioned around the right ear using double-sided adhesive tape and using a small amount of conductive gel. 3000 clicks of alternating polarity were presented monaural using an in-ear microphone at an average rate of $\sim$ 10Hz per condition. A uniformly distributed random silence jitter was added to the stimulus of max 10%. The clicks had a duration of 80μs and had a 100dB peak-equivalent sound pressure level. Both the clicks and triggers were generated in MATLAB at a sampling rate of 48kHz and the triggers were collected on the motherboard of the system to store these together with the captured EEG data.

The ABR data was processed offline after reading out the data from the SD-card. This processing consisted of a filtering step (LP filter with 1500Hz cutoff and HP filter with a cutoff frequency of 100Hz, both filters are Butterworth filters of order 4), epoching the first 20ms of data following a trigger and the removal of the epochs containing the largest occurring amplitudes to eliminate recording artefacts (15%). The remaining epochs were averaged to find the mean ABR signal, as well as bootstrapped [13] to find the confidence interval and the statistical noise floor, all of which are depicted in Fig. 2.

IV. Results

A. Specifications

Table 1 compares the two investigated EEG systems, and shows that the performance of our proposed system is on par, or exceeds the performance of the reference BioSemi device. Three performance metrics are further discussed below.

TABLE I

Comparison of specifications between the system designed in this study and the reference BioSemi ActiveTwo Mk2 system.

Specification	Proposed System	BioSemi [16]
Maximum sample-rate	16000Hz	16384Hz
Sample rate accuracy	<200ps	<200ps
Sampling skew	25ps	<10ps
Bandwidth (-3dB)	3400Hz	3200Hz
Total input ref. noise	0.5μVrms	2.0μVrms
Distortion	<0.001%	<0.1%
Resolution	24-bit	24-bit
CMRR (at 50Hz)	>110dB	>90dB

1) Bandwidth: We assume that both the internal filtering of the ADS1299 and the anti-aliasing filters in front of the ADC are first order filters to derive the bandwidth of the system. Based on our used components, we thus determined the 3dB cut-off frequency at 3297Hz. To obtain the real bandwidth, a linear frequency sweep was performed by connecting a wave generator to a copper brain model connected to the system, while determining the input/output gain. This resulted in an actual bandwidth of 3400 Hz.

2) Total input referred noise: To calculate the noise inherent to the design of our system, we calculate the bandwidth-related noise contributions for three prominent noise sources within the device, all in root mean square voltages: For the low-noise amplifiers (INA828) this is 0.491μV, the RC-filter gives 0.006μV and the ADS1299 contributes 0.217μV. It should be noted that the noise components of both the RC-filter and ADC were calculated with reference to the input by dividing the total noise component by the used amplification gain. The total system noise then amounts to:

$$V_{RMS,total} = \sqrt{0.491^2 + 0.006^2 + 0.217^2} = 0.537\mu V \quad (1)$$

For uncorrelated noise sources. This noise value was also confirmed by shorting the input channels and calculating the input-referred RMS noise on the received data. This gave 0.503μV, matching the theoretical value.

3) Harmonic distortion: The harmonic distortion is defined here by the second harmonic and the ratio to the fundamental frequency (1kHz). The wave generators used during these measurements could not operate below 500μV

however, hence the found distortion percentage of $<0.001\%$ can be seen as an overfitting, and requires additional testing.

B. ABRs

When comparing the result of Fig. 2 to a reference ABR measurement also performed with cEEGrids [13], it can be noted that the Wave-I and Wave-V (i.e., two of the characteristic five (I-V) deflections within the first 10 ms after stimulus onset, originating from ascending relay stations of the auditory pathway [17]) depicted here share a similar time delay as can be expected for a 100 dB peSPL click [18]. The obtained signal amplitudes also fall within the same order of magnitude $\sim 0.20\mu$V, especially when considering the confidence interval. The measured noisefloor of Fig. 2 is slightly larger at about 0.08μV instead of 0.06μV, and this can be explained by the difference in sensor technology (cEEGrid vs conventional cap-EEG). To confirm this, additional measurements were performed in similar conditions for a BioSemi system measurement with cap-EEG (using the same electrode and references as mentioned in [13], i.e., DRL on nostril), as well as for the BioSemi connected with the cEEGrid (reference on the central forehead, DRL on nostril) and the proposed system explained here. The obtained noisefloor of the cap-EEG-measurement matched that shown in figure 1.B of [13]. The BioSemi measurement, connected with cEEGrid electrodes had a noisefloor that is more conform with the noisefloor (0.10μV) shown in Fig. 2, as could be expected.

V. Discussion - Next Steps

In summary, although we achieved similar specifications for our system compared to the reference method in the performed measurements, some wariness is required. All measurements were performed without connection to the power net and the system was placed in a electrically-shielded booth. Additional measurements should prove that this system is indeed able to achieve comparable, or at least viable, measurements outside the lab environment, where additional noise will be inevitable (e.g. movement of the subject, electric interference). A pilot study was done to investigate the portability and functioning of the system while outside, and this showed that the sensor connection remained intact and that the obtained signals where still within the expected range.

Future work includes the merging of the 4 physical components into a single device that is smaller and this will increase the portability. Additional functionalities can also be added to the device, e.g. feature extraction and data analysis stage to be executable in parallel with the real-time EEG capturing functionality. The used ADS1299 chip can also be daisy chained to add additional electrodes to the system, hence a binaural extension, using 2 cEEGrids (one around each ear), is well within reach of this project.

VI. Conclusion

In this study we proposed a new wearable hardware design for EEG acquisition based on around-the-ear cEEGrid electrodes. eight EEG channels can be collected, amplified, filtered and converted to a digital signal by the ADS1299 chip before being transmitted to and stored by an ESP32 microcontroller. This system, able to achieve sampling rates well above the desired frequencies for auditory brainstem measurements (16kHz), while maintaining a low-enough noise floor, showed to match the specifications of a state-of-the-art cap-EEG acquisition system that is the ActiveTwo Mk2 BioSemi. We were able to collect and process a standard click ABR, clearly showing to grasp both the Wave-I and Wave-V in response to this stimulus. Our system thus has the capability of opening new avenues for auditory EEG based hearing diagnostics, damage prevention and treatment follow-up.

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