The development of Arduino-based low-cost wireless modular device for brainwave acquisition

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Abstract. Brainwave is widely used as an indicator of brain activity and can be detected by electroencephalography (EEG). The development of EEG device has become more advanced along with the invention of low-cost tiny electronic modules and wireless technology. This research aimed to develop a low-cost wireless modular device for brainwave acquisition based on Arduino microcontroller. The system was designed into sensor block for brainwave receiver and conditioning, and mainboard block for data processing. Dry-active electrode was developed as the sensor, followed by preamplifier module which was also installed at the mainboard part. Active filter and DRL circuits were developed on the mainboard part. Arduino UNO was used as the main processor of the device. The developed modules were then evaluated using signal generator to examine the module characteristics and consistency. As the result, the preamplifier module was detected to reach 40.34 dB on gain ability. The cutoff frequency on the active filter module was calculated on 31 Hz. Furthermore, Arduino UNO was identified to have a consistency on input and output voltage.

1. Introduction

Electroencephalography or EEG has been known as one of the most important tools for diagnoses of brain diseases and abnormalities. Along with its roles on increasing diagnostic accuracy, EEG is also very reliable as a first-line method on neurological diagnostic for its fast and practical operation [1]. Therefore, when other factors such as a relatively cheap operational cost and zero invasiveness procedure are added as a consideration, EEG could straightforwardly become the frontline procedure in the assessment of brain disease and disorder.

Those factors come with several drawbacks. As the brainwave is acquired through the scalp, the common pitfall is the electrode displacement which abruptly alters the signal quality [2]. The electrode wire is also a challenge as it could be a source of electromagnetic induction and is highly sensitive even to relatively small static charge [3]. The use of wet electrode that requires conductive gel or liquid becomes another challenge. Drying gel or liquid is known to be another source of variability and limit the length of simultaneously recording time [4]. Various solutions are currently provided in many EEG systems, such as gold-coated electrodes, headset design, and numerous additional devices and modules. All are excellent but tend to be less portable and costly.
Therefore, alternatives were needed to overcome those pitfalls yet still have a moderate portability and affordability. This study aimed to propose an alternative system for brainwave recording. A wire-free dry-active electrode was chosen as a sensor. To reduce the system cost, Arduino UNO was chosen as the main processing unit since its reliability has been tested on various health and medical monitoring system, such as for lymphatic biomechanics study [5], heart rate monitoring [6], electrocardiography [7,8], etc. In addition, Bluetooth connection was utilized as the connection to the computer for data communication purpose. Module testing was also conducted to evaluate the characteristics and consistency of each module.

2. System design
Hardware system design was divided into sensor and mainboard blocks. Sensor block serves as brainwave acquisition and conditioning for further process. Mainboard block contains component for data conversion, processor, communication component, battery and component for further signal processing. The latter block was packed in a small box. Both blocks were then attached to the headband. The system’s diagram block is presented in figure 1.

![Figure 1. Block diagram of the system.](image)

System was designed to work with Bluetooth module as the wireless facility and SD card as an additional storage. Data flow in the system comprises of three main databases; those are data command, status and ADC (analog to digital converter) and timing data. System is triggered by a command from the computer or android device. The system then sends back a response as a status data, which is used as parameter to start the brainwave acquisition process.

3. Modules design and development
The system was designed to be modular or comprised by several separated modules; those are dry-active electrode as a sensor and several processing components as non-sensor modules.

3.1. Dry-active electrode and preamplifier modules
The source of electrode material was taken from pin header which is commonly affordable and used as connector in electronic circuit. The surface of pin header was coated with silver (Ag) to improve the skin-electrode contact so the impedance could be reduced. Pin header was attached to the circle-shaped PCB with 2 cm in diameter. As shown in Figure 2, the pin header was warped horizontally so the pin rods were conveniently contacted to the skin.

The signal amplification circuit is the basis of preamplifier component. Since EEG has a voltage lower than a millivolt, this circuit is really important for the next processing step. INA118 instrumentation amplifier was chosen based on its relatively cheap price and its ability to amplify the signal 100 times. In this case, the signal can be theoretically amplified from 10-100 µV to 1-10 mV. Less than 100 times would be too small, while more than that could lead to output voltage saturation.

To improve the signal accuracy, preamplifier module was supported by Driven-Right Leg or DRL. DRL has been commonly used to reduce noises by common-mode voltage [9,10], especially power-lines interference [11], which is a notable source of noise for many bioelectric recording systems. For this study, the DRL circuit was adapted from ModularEEG design [12].
3.2. Active filter
Since brainwaves are detected at a low range of frequency, a second-order low-pass filter (LPF) was implemented on the filter circuit to cut the frequency. Butterworth filter was chosen as the filter response. This filter class is very common to be employed in electrophysiology because of its linear response so no ripple is generated [13,14].

Butterworth filter was implemented on the circuit using a certain topology. For a second-order filter, there are several topologies which can be used to implement the filter. In this study, Multiple Feedback (MFB) topology was chosen for its moderate stability and need on fewer passive components compared to other.

3.3. Arduino UNO
The main processing unit used in this study was Arduino UNO. This device is supported by ATmega328T microchip as the microcontroller. The device has a built in 10-bit analog to converter (ADC), which has a crucial function on the signal acquisition and processing. The existence of built ADC on the device made the system less complicated and fewer components.

Arduino UNO is also supported by several communication peripheral for serial data transmission. Two of them, which are Universal Asynchronous Reception and Transmission (UART) and Serial Peripheral Interface (SPI), were employed respectively for Bluetooth communication and transmission data to SD Card. Bluetooth was chosen for its low power consumption compared to WiFi, so that the battery mass and volume can be reduced. Bluetooth was only needed as a slave operation mode; hence Bluetooth HC-06 was an optimum choice for its relatively low price and easy connectivity. For the SD card module, an SD card slot and a voltage converter of 5 V to 3.3 V was installed. A common SD card can be employed using this module.

4. Module testing
As the main signal processing modules, preamplifier, active filter, and Arduino UNO were tested. The testing was conducted using a signal generator and an external power supply. Digital oscilloscope GDS 1102A-U (GW Instek, New Taipei City, Taiwan) was used for the measurements.

4.1. Preamplifier gain stability
The testing was conducted using frequency 10 Hz to 1000 Hz as the input from signal generator to find the gain stability of the preamplifier. Note that the testing was intended to find stability on higher frequency range and, if any, the slope existence, so the gain stability on frequency less than 10 Hz was not included in this paper. The testing result is presented by figure 3.

The result shows that the maximum gain detected on the range 10-1000 Hz was 40.34 dB, which was measured on 10 Hz. The gain was found stable on around 40 dB and the slope was not found.
across the frequency range. This result means that for the upper EEG frequency, the designed preamplifier module has a stable capability on amplifying the detected signal.

![Graph showing preamplifier gain across frequency range from 10 to 1000 Hz](image)

**Figure 3.** The preamplifier gain on the frequency range of 10-1000 Hz.

4.2. **Active filter characteristics**

The characteristics measurement of active filter was conducted using signal generator. Similar to the preamplifier gain measurement, this testing was also conducted on the frequency range of 10-1000 Hz. The result is presented by figure 4.

![Graph showing active filter characteristics with a cutoff frequency around 31 Hz](image)

**Figure 4.** The active filter characteristics represented by the cutoff frequency on around 31 Hz.

There are different ranges of EEG frequency. Excluding gamma waves, the maximum frequency ranges of EEG are vary from 25 Hz to 45 Hz, which is the upper limit of beta waves. Several authors stated beta waves are ranged on 13-30 Hz [15,16], while some other stated the maximum frequency of 40 Hz [17]. Theoretically, the gain should cover the maximum range of needed frequency. Note that the filter was designed to detect beta waves as the highest frequency band.

From figure 4, it is found that the active filter has a cutoff frequency around 31 Hz. This result shows that the active filter would work very well for the maximum range of 25-30 Hz. However, the module needs more improvements to work on higher range of EEG frequency.

4.3. **Arduino’s ADC consistency**

Calibration is an important procedure when data conversion process is involved in the system. In this study, such process was handled by ADC. The ADC calibration on a range of input voltage was
intended to evaluate the ADC consistency, which has a vital role on brainwave reading. The reference voltage was selected on 2.5 V to avoid a truncated input voltage. To conduct the testing, the power supply was employed as the input voltage while the output was measured by the oscilloscope. The reference voltage was set on 2.5 V. This voltage value was chosen to avoid any cutting on the input voltage.

Figure 5 shows the result of ADC consistency measurement. From the result, the coefficient of determination was calculated on 0.9994. This result shows the very high quality of Arduino’s ADC consistency. A linear correlation was observed between the input and output voltages, which respectively represent analog and digital voltages. Since brainwaves are detected as a very small voltage, a good consistency of ADC output would give an accuracy detection of EEG signal.

5. Discussion
From the physical perspective, the developed modules were found to be working well for brain signal acquisition, which means that the testing results represent the range of EEG’s higher frequency bands. The yielded gain of 40 dB on the preamplifier module is almost similar to the result from [18], which is around 39.95 dB and used pseudo open-loop architecture. Another developed device used a basic differential amplifier [19], which is much simpler compared to the proposed preamplifier; however, the filter gain was 21.8 dB. The gain of 40 dB is considered to have an optimum signal-to-noise ratio (SNR) with less risk of saturation.

Other modules are regarded to be well developed. The designed electrode would be a good fit for a low-cost wireless portable EEG system. It is really cheap, quite easy to develop, and comfortable to be placed on the scalp. Compared to the commercially available dry comb electrode used on [20], the developed electrode in this study can be subjectively regarded as the optimum design for both hairless contacts to the scalp by pin headers and comfortability factor. The active filter and Arduino UNO’s ADC are also observed very prospective as the filter and main processor of the developed EEG system. In addition, the modular system is regarded beneficial on a condition which needs module replacement and upgrading.

However, some improvements and further studies are needed. A smaller electrode is needed to acquire brainwaves from a more specific brain area. The testing on lower frequency is needed on preamplifier and active filter modules. An increase in dB gain would also give a better detection on lower brainwave amplitude, as well as a higher cutoff frequency. In addition, several peripheral components, such as a power supply and communication modules are needed to be designed effectively to cover the needs of Arduino and other components but still has a low-cost factor and small enough to put on the device.
6. Conclusion
The modules show a promising wireless EEG system with moderate capability, which in this study, for a stability on signal acquisition of 10 Hz and above. The modular system is also considered to be affordable and maintainable. Further research and development is needed to improve the system’s quality and accuracy, as well as more testing on a lower range of frequency.

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