

Design and hardware optimization of a modular EEG acquisition system for BCI applications

Vanessa S. Nazakova

Abstract: *The proposed EEG hardware is intentionally designed as an open-hardware, costeffective module utilizing widely accessible commercial-off-the-shelf (COTS) components. This approach aims to meet basic research requirements for Brain-Computer Interface (BCI) studies without the prohibitive costs of clinical-grade instrumentation. Several configurations and readymade modules have been experimented with in order to discover the best approach for this project. Using a high-precision instrumental amplifier provides a scalable and affordable entry point for researchers and students focused on neural command mapping and BCI signal processing. The system supports up to 8 channels with resolutions ranging from 16 to 24 bits and sampling rate up to 1 kHz, incorporating instrumentation amplifiers, active shielding and noise suppression, with wireless connectivity for real-time signal acquisition and visualization.*

Keywords –*brain-computer interface, EEG, instrumental amplifier*

Проектиране и хардуерна оптимизация на модулна ЕЕГ система за изграждане на приложения, използващи мозъчно-компютърен интерфейс (Ванеса С. Назъкова). Предложеният ЕЕГ е проектиран като модул с отворен хардуер и ниска себестойност, използващ широкодостъпни комерсиални компоненти (COTS). Този подход цели да отговори на основните изследователски изисквания за проучвания в областта на мозъчно-компютърния интерфейс (BCI), заобикаляйки високите разходи за клинично оборудване. Направени са експерименти с няколко конфигурации на готови модули с цел намиране на най-подходящия подход за настоящия проект. Използвайки прецизен инструментален усилвател, модулът осигурява мащабируема и достъпна отправна точка за изследователи и студенти, работещи върху невронни команди и обработка на BCI сигнали. Системата поддържа до 8 канала с разделителна способност от 16 до 24 бита и скорост на дискретизация до 1 kHz, включваща инструментални усилватели, активно екраниране и потискане на смущенията с безжична свързаност за запис и визуализация на сигнали в реално време.

Introduction and motivation

Historically, the development of electroencephalography (EEG) began with Hans Berger's discovery of the brain's electrical activity in 1929 [1], followed by its experimental validation by Adrian and Matthews (1934) [2] and the later standardization of electrode placement through the "10–20" system introduced by Jasper (1958) [3]. These milestones established the fundamental principles for measuring and interpreting bioelectrical signals from the human brain.

In modern applications, however, the focus has shifted from purely clinical observation to the development of compact, high-resolution, and portable

acquisition systems. This transition introduces new engineering challenges, particularly the need for low-noise analog front-end design and stable power supply, which are critical for distinguishing weak EEG signals from environmental and electronic interference [4].

In this context, the present work is focused on the design and optimization of an open hardware, low-cost, low-power EEG acquisition system based on ready-to-use modules and minimal subdesign. The primary objective is to achieve reliable ECG/EEG signal acquisition with maximum accuracy and minimal noise levels [5][6][7], using accessible instrumentation amplifiers and embedded platforms.

A secondary objective is the real-time utilization of the acquired signals in a Brain-Computer Interface (BCI), enabling the mapping of cognitive activity to control commands through key-binding mechanisms.

Design and development of an accessible EEG acquisition module for consumer biofeedback systems

The developed module is designed as a compact and accessible platform for acquiring and processing bioelectrical signals, with a focus on reliability, scalability, and ease of integration into consumer applications.

The system is intended to provide:

Simultaneous acquisition of up to 8 EEG/ECG channels with high resolution (16–24 bits) and sampling rates of up to 1 kHz, enabling accurate recording of low-amplitude biopotentials [8].

- An embedded microcontroller-based interface (Arduino/ESP platform) with integrated web functionality for real-time signal monitoring and wireless connectivity to computers and mobile devices.
- Dedicated software tools for signal recording, processing, and machine learning-based recognition of bioelectrical patterns associated with user motor activity [9].
- A software driver enabling the implementation of a Brain-Computer Interface (BCI) as a Human Interface Device (HID), allowing mapping of detected EEG patterns to control commands, including interaction with video games [10][11].
- Versatility for use in multiple biomedical applications, including EEG and ECG/EMG measurements.
- Accessibility-oriented design, targeting users with limited mobility by providing an alternative method for human–computer interaction without reliance on traditional input devices such as keyboards, mice, or controllers.

Prototyping

The microcontroller performs initial data handling and transmits the acquired signals to a personal computer via TCP/IP, or alternatively provides realtime monitoring through a built-in web interface. This enables flexible access to the data from both desktop and mobile devices.

On the host computer, dedicated BCI software processes the incoming data stream and maps

recognized signal patterns to predefined control actions, such as movement, jumping, or object selection in a virtual environment. This functionality is implemented through a mechanism analogous to keybinding systems, where specific EEG patterns are associated with corresponding keyboard commands.

To ensure reliable and user-specific performance, a calibration procedure is applied. During this stage, the system learns and adapts to the individual EEG characteristics of the user, improving classification accuracy under real-world conditions.

The module is designed to operate with both dry and wet electrodes, providing flexibility in terms of usability, setup time, and signal quality.

Project evolution

The project evolved through several stages, starting from a university-developed ECG 10bit module and progressing through 13-bit and 16-bit implementations to a final 24-bit high-resolution system.

First version — ESP8266 + MCP3301 (13-bit, 2 channels)

In Fig.1 is shown a ECG/EEG signal recording system based on an instrumentation amplifier AD623 (gain $\times 50$, second stage $\times 250$). [12][13]

- A 13-bit ADC MCP3301 was used in pseudodifferential mode. [14]
- SPI interface communication, based on a platform developed in the Telecommunications Department of New Bulgarian University. This represents an incremental innovation that proves functionality.
- The existing 10-bit EMG/ECG module was upgraded with a 13-bit ADC and an additional analog stage, making it suitable for EEG.

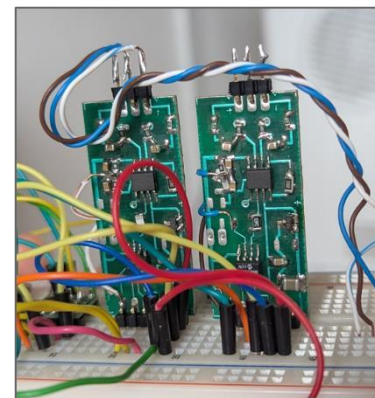


Fig. 1 Dual InAmp and 13-bit module with MCP3301 and SPI communication port.

Second version — ESP8266 + AD7680 + ADG819 (16-bit, 2 channels)

- SPI port communication was replaced with a WiFi ESP8266 module, enabling:
- Visualization via a built-in web server,
- JavaScript graphs via WebSockets.

This makes the module convenient to use, making it accessible from a mobile phone.

Extended 16-bit version

An interface with extended dynamic range was implemented by integrating a 16-bit SAR ADC AD7680 with a low-noise ADG819 multiplexer, making the system suitable for two-channel ECG/EMG/EEG recordings, with a sampling rate of up to 10 ksp/s for each of the two channels. This turns the module into a universal portable bioinstrumentation system. (Fig. 2)

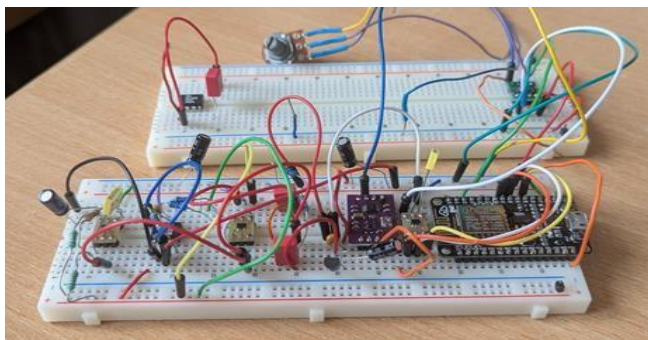


Fig. 2 Upgraded version with ESP8266 microcontroller and 16-bit SAR ADC AD7680 with a controlling low-noise multiplexer ADG819, making the system suitable for a two-channel EMG/ECG/EEG Holter system.

A new analog section with separate reference power supplies was added. A buffered and stabilized virtual ground is used. The circuit operates stably without active shielding and a right-leg drive. In this implementation, the low-noise amplifier INA333 was tested, with improved input parameters and sensitivity compared to the older AD623.

The controller firmware implements digital filtering, packetization, and data transmission via the built-in Wi-Fi interface. Data transmission is implemented using the OpenEEG protocol, supporting up to 6 16-bit channels at a sampling rate of 250 Hz.

Third version

24-bit, 8-channel ADCs — ADS1256 and ADS131M08 — enabling simultaneous conversion and

digital filtering. Both modules can be found on low-budget ready-made boards integrating:

- Separate reference power supplies,
- Stability without the need for active shielding,
- An eight-channel extended platform.

For the analog interface, each channel is buffered via AD623 or INA333 [15], enabling comparison and optimization of their noise parameters.

The design includes two-stage analog amplification, sampling frequency up to 30 kHz per channel, reliable multiplexing, and stable measurement of low-amplitude EEG signals. The sampling rate depends on the type of ADC module; the maximum achievable speed is valid for the simultaneously sampling module. At higher speeds, the effective resolution drops to 19 bits per channel. The result is a compact, energy-efficient, and low-budget eight-channel EEG system, suitable for mobile applications and long-duration recordings.

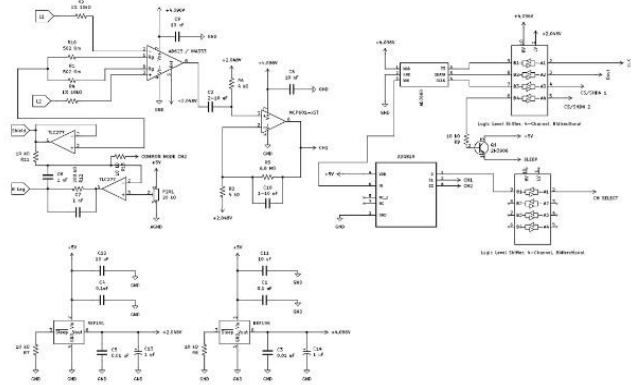


Fig. 3 InAmp module, including first and second stage amplifiers, active shield driver and right leg drive, with power supply and optically isolated 16-bit ADC converter.

Initially, the ADS1256 was chosen for its low cost and compact board size. The module has 8 input channels providing 24-bit precision with an effective noise-free resolution of 18 bits at sampling rates of 1.45 kHz.

The disadvantage of the module is that a full cycle of the built-in filter must be awaited when switching between input channels. This time varies between 0.21 ms and 60.01 ms depending on the sampling frequency.[16]

This limitation restricts the maximum sampling frequency per channel to between 595 Hz and 231 Hz. This makes it suitable for basic measurements but cannot achieve the high frequency resolution needed to detect gamma waves.

The EEG module based on ADS131M08 offers high effective resolution of approximately 20.3 bits

(Dynamic Range — 113 dB) at the configured settings. The chip provides simultaneous sampling of 8 channels (Simultaneous 8-ch $\Delta\Sigma$), which is especially important for correct measurement of biosignals such as EEG and ECG, where phase delay between channels must be avoided.

General conclusions

When using ready-made modules, the following characteristics were identified, which every developer must consider to avoid errors. Initially, two different manufacturers of ADS1256 modules were selected. It was found that the PCB design of the first module follows basic requirements for separating analog from digital ground, but uses a drastically simplified power supply circuit, which leads to degraded parameters and below 20 bits of effective resolution. The second ADS1256 module uses a far more complex power supply scheme and, despite its worse PCB design, achieves an effective resolution of approximately 22 bits.

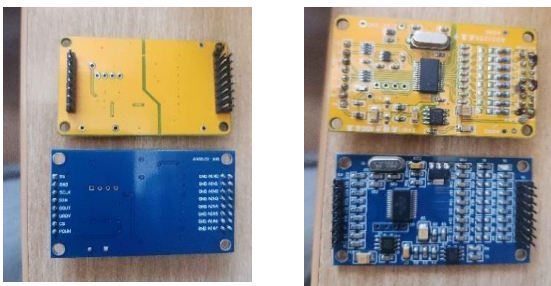


Fig. 4 Two different 24-bit ADC modules ADS1256, showing that different suppliers use different criteria for manufacturing high-resolution systems.

The third module, using ADS131M08, has an unsuitable power supply reference source, which in commercial use would require replacement of the chip with a compatible one. The main problem with this board is that on channel 8, the design reverses the differential inputs, which is not correctly reflected in the board's silkscreen.

The general conclusion when using such readymade modules is the mandatory verification and reengineering of their schematic before any connection to measurement equipment. Nevertheless, the price and relatively good quality — especially for high-resolution analog-to-digital converter implementations — are the primary factors influencing the choice made.

Selecting instrumentation amplifiers

Due to availability, the instrumentation amplifier AD623 was used in the project. It supports supply

voltages between 2.7 V and 12 V, [17] which is an advantage when developing ECG/EMG interfaces. The amplifier has 90 dB CMRR and an offset voltage of 100 μ V.

A more modern choice is the INA333, which consumes 10 times less current, has 4 times lower input offset, and provides up to 100 dB CMRR at operating voltages from 1.8 V to 5.5 V.

It should be noted that both amplifiers require a path for the input bias current to operate correctly, even in DC measurements. The INA333 uses CMOS technology and requires approximately 70 pA of input current, allowing 20 M Ω input resistors to be placed without creating significant offset. For the AD623, this current is 17 nA since the amplifier uses bipolar transistors, and resistors are in the range of 1–10 M Ω to virtual ground. This is not noted by manufacturers of Open Hardware EEG systems, yet it is key to ensuring minimum functionality of the circuit in amateur use in home and heavily noisy environments.

The circuit uses 2 k Ω / 0.2 W input protection resistors, providing immunity up to approximately 20 V input voltage exceeding the 5 V supply. Similar resistors are used in the OpenEEG project. Additional protection is provided by BAV199 diodes at the inputs and outputs of the amplifiers connected to the patient. The device is not intended for medical use, and power supply isolation issues are resolved through wireless connectivity and battery power.

Active shield driving

Since inexpensive cables are used, a method of active shielding is applied to the cable braid, onto which the same potential extracted from the summing node of the instrumentation amplifiers' input signals is applied. This approach neutralizes the capacitance between individual conductors and the cable shield.

Most EEG practices use single unshielded wires to avoid the microphonic effect and signal attenuation from capacitance between the signal conductor and the cable braid. This manifests as large spikes when recording signals from the patient's head.

Since the presented module is designed for amateur use, active shield driving suppresses this effect. The active shield also prevents the triboelectric effect, which arises from friction of the insulation within the wire conductors. The circuit uses passive electrodes for simplicity of wiring, and because high-impedance electrodes are used, the cable would be extremely sensitive to any type of external capacitance. This further reduces requirements for contact gel when the

contact dries or undergoes microscopic displacement. The greatest influence of active shielding is on CMRR.

Suppression of radio frequency interference Fig. 5 shows an illustrative example of using an input capacitive filter to suppress radio frequency interference before the signal is applied to the instrumentation amplifier. [18].

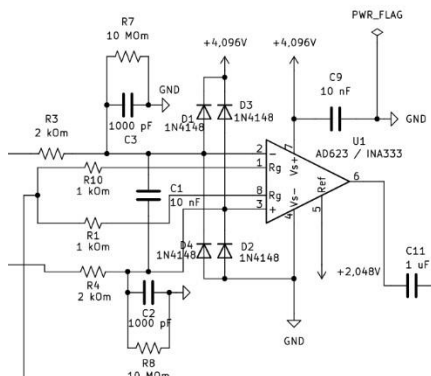


Fig.5 InAmp high-voltage clamping diodes and capacitive RF suppression protection

The selection of input capacitors requires that the capacitors from the two differential inputs to virtual ground be 10 times smaller in value than the main one. The selected components provide suppression of high-frequency radio interference at 77 kHz. Since capacitors with tolerance below 5% are difficult to order, manual selection of the most closely matched values is performed before assembly. This is done to ensure equal input amplitude-frequency characteristics across all channels.

When dealing with higher levels of interference, increasing the input capacitance is not recommended, as this leads to poor amplification of weak EEG gamma signals. [19]

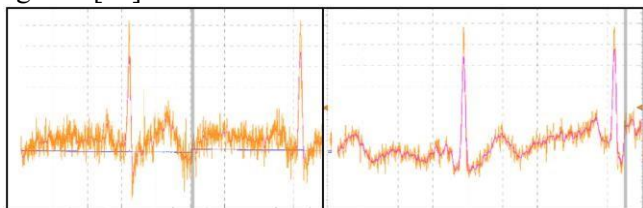


Fig.6 ECG signal in the presence of high radio frequency interference, respectively without and with filtering capacitors at the input.

Power supply interference

During experiments, a regular laptop was used, whose switching power supply is a source of high-frequency interference with broad spectrum and periodicity. Oscilloscope traces were captured from the +5 V regulator of the analog section with mains power

connected and disconnected. To prevent such interference from coupling into the precision instrumentation amplifiers and ADC module, a USB optical isolator and battery power supply are typically used. With a Wi-Fi connection, this is not necessary. (Fig.7)

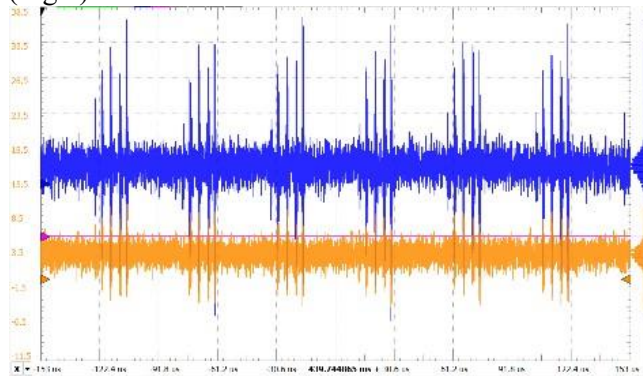


Fig.7 Typical switching computer power supply noise

Right leg drive (RLD)

A standard circuit is used for common-mode interference suppression in the patient, with the input isolated at DC, and a potentiometer can be placed in the feedback loop to set the gain in the range of 10–20 times. (Фиг.8)

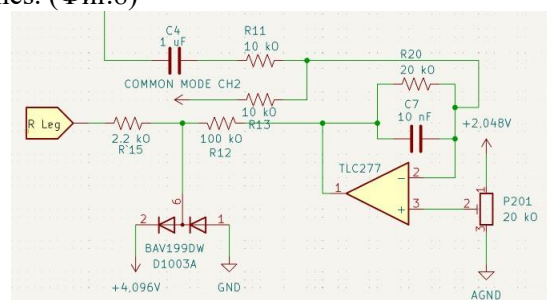


Fig.8 ECG/EEG Right Leg Drive Schematic

The role of this module in the circuit is to create an active Vref that causes the virtual ground of the measurement amplifier to "float" in common mode with the mains interference. The amplifier injects a counter-phase microcurrent into the patient via an additional electrode, attached to the right leg in ECG or to the ear in EEG. The feedback loop includes a 0.5–1 nF capacitor to suppress high-frequency noise.

Fig. 9 shows the 50/60 Hz common-mode input signal with distortions from a solar inverter and the counter-phase signal at the RLD driver output. Impulse interference from unbalanced inverters and switching power supplies is very difficult to remove from the useful signal. This seriously hinders the correct detection of EMG signals, and is especially problematic in the detection of EEG gamma waves.

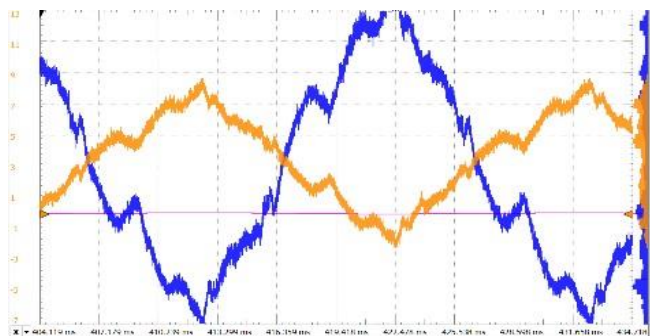


Fig.9 Common mode powerline noise and 50 Hz counterphase driver signal. Interference from solar inverters and air-conditioning is clearly visible.

Fig. 10 shows the effect of applying RLD, as well as randomly superimposed mains interference and interference from the laptop's switching power supply.

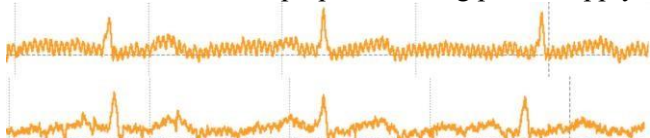


Fig.10 Powerline noise compensation without and with RLD. Muscle tremor is visible.

Data exchange protocol

The current implementation uses the EEG-SMT protocol, supporting up to 6 16-bit channels. The protocol stack includes: two synchronization bytes, protocol version, and packet sequence number used for detecting lost data. The data format is Big Endian (MSB first, followed by LSB). By default, the protocol operates at 57600 bps with a sampling frequency of 256 samples per second. The total packet length is 17 bytes and is sent every 3.91 milliseconds. The data format is 8 bits, 1 stop bit, no parity (8N1). The protocol is used in the following software: ElecGuru, OpenViBE, and BrainBay. A Bluetooth version also exists. This makes the protocol and module universal and convenient for integration with Python, C++, and Java programs. [20]

Similar commercial Open-Source products

The *EEG-SMT* module is manufactured by a Bulgarian company, with the design originating from the OpenEEG Project, which allows the creation of a modular measurement interface with up to 6 channels. [21] The module allows connection to a personal computer via serial interface or USB converter FT232RL. Implementations with up to 16 channels exist for this project. [7] The module uses the EEG-SMT protocol. [22]

OpenBCI Cyton represents the highest class among open-source platforms and uses specialized chips for precise 24-bit measurement of brain activity. [23] The system provides full access to raw data and is fully compatible with professional software for scientific analysis, making it a standard in the research community.

NeuroSky MindWave is a budget consumer device with a single channel, designed primarily for entertainment and basic meditation applications. It uses a closed architecture and a simplified interface that converts complex waves into ready-made concentration indicators, but its lack of resolution makes it unsuitable for serious work.

Emotiv EPOC is a designer wireless device with a fixed number of channels, distinguished by quick setup and a professional appearance for marketing purposes.

Backyard Brains SpikerBox is a simplified educational module created for school demonstrations of basic neurophysiology principles.

EEG processing software

Two software products are used for processing signals from the developed hardware — *OpenViBE* and *BrainBay*. (Table 1.)

Table 1

Comparison between *BrainBay* and *OpenViBE*

Feature	BrainBay	OpenViBE
Complexity	Low	High
Number of channels	Optimal up to 4–6	Unlimited (32+)
LSL support	Limited / via plugins	Native
Visualization (Topographic maps)	Basic	Professional
Processing	Linear	Parallel and matrix

BrainBay is lightweight, straightforward, and very intuitive for a small number of channels. Everything happens on a single screen view. Its extremely low resource consumption makes it fast and lightweight. It is convenient for quick hardware testing with biofeedback games. It is not suitable for managing many channels due to GUI limitations. It offers limited capabilities for complex signal filtering and does not support modern protocols such as LSL well.

OpenViBE is designed for professional scientific work and complex Brain-Computer Interfaces (BCI). The interface is split into two parts: Designer (where a

logical diagram is built with blocks) and Acquisition Server (for managing LSL and hardware connections). It supports 32+ channels without performance loss. It has built-in complex algorithms for real-time detection of P300 waves, motor imagery, and frequency analysis. It is considerably more complex to use. [24]

Testing and results

Extensive tests were carried out:

- Comparison of different instrumentation amplifiers (AD623 and INA333),
- Noise measurements and frequency response evaluation,
- ADC accuracy evaluation in different operating modes [25]
- WiFi communication and WebSocket visualization testing, [26] [27]
- BCI experiments with real users: cardiogram, "concentration", "blinking", motor imagery.

The project has achieved:

- A fully functional 8-channel mobile EEG module,
- 6–24-bit resolution across different versions,
- Stable and repeatable measurement of low-amplitude biopotentials,
- A precise calibration and machine learning process,
- A WiFi-based web interface for real-time visualization,
- Successful ECG, EOG, and EEG measurements. (Fig.11) [28]

The project's innovation manifests in several directions. First, the system uses entirely accessible and low-budget components for every part of the build — from the microcontroller and 16-bit ADC modules to the dry EEG electrodes and 3D-printed prototypes. This makes the development suitable for mass application and facilitates future expansion. The practical design, compatible with a headband without requiring implants, enhances safety, comfort, and the possibility of daily use both in laboratory and home environments.

The project is of significant social value, as it offers an alternative means of interaction with the digital environment for people with motor disabilities. By interpreting specific brainwave patterns as commands, the system can serve as a means of controlling games, software, or assistive devices. This opens new possibilities for inclusion, communication, and autonomy.

From an educational standpoint, the project demonstrates the power of open hardware (Arduino, ESP8266) and modern BCI technologies. It serves as a solid practical platform for training students and young engineers in the fields of biosignals, digital processing, and embedded systems. This contributes to the development of specialists in electronics, telecommunications, and medical technology.

The results obtained demonstrate successful processing of EEG signals with a multi-channel architecture, 16-bit resolution, stable operation of the analog stages, digital filtering, and reliable wireless communication via WiFi WebSockets. The prototype demonstrates real-time control of game actions via brain activity, confirming its applicability.

The potential for technological development is significant. Plans include expanding the system to an additional 8 channels (16 total), enabling more precise analysis of brain maps and control of more complex games or applications with more commands.

Introduction of machine learning for higher recognition accuracy is envisioned, as well as integration with other devices such as robotic systems or wheelchairs.

In its entirety, the project represents an accessible, socially significant, and highly innovative platform with great potential for development in medicine, rehabilitation, gaming, and education.

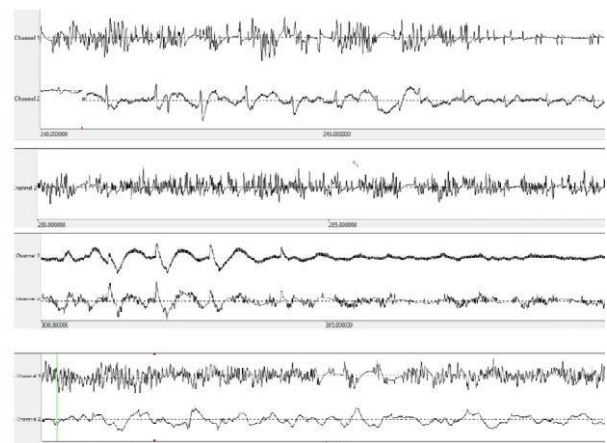


Fig.11 Different EEG signal readings in OpenViBE, captured from various points on the head

Conclusion

The project has high potential for real-world applicability in healthcare, education, rehabilitation, social services, and beyond. It is conceived for application in assisting people with motor impairments. Through the use of EEG signals, the system enables control of computers, software, or games without the

use of hands. This is important for users who cannot work with traditional interfaces such as a keyboard, mouse, or joystick. The technology has the potential to be extended to controlling wheelchairs, robotic assistants, and home automation systems, thereby supporting independence and quality of life.

The project also has educational value, serving as a practical platform for training students in electronics, biotechnology, signal processing, and artificial intelligence. Through the combination of hardware, software, and machine learning algorithms, it supports the development of young engineers and researchers, preparing them for the modern demands of industry.

In the entertainment industry, the project offers a new type of interaction — controlling video games and virtual environments through thought.

From an ecological and economic perspective, the system is architecturally built on modular, interchangeable components, ensuring repairability. It uses energy-efficient and readily available components. This reduces maintenance costs and enables wider deployment without a significant resource footprint.

Acknowledgment

The author would like to express sincere gratitude to the staff of CEEC for the opportunity to publish this work. This publication was made possible through the "Project of the Year" competition, organised by CEEC, in which the presented project was selected as the winning entry. The author is honoured by this recognition and thankful for the support and encouragement it represents.

REFERENCES

- [1] Berger, H. Über das Elektrenkephalogramm des Menschen. *Archiv f. Psychiatrie* 87, 527–570 (1929). <https://doi.org/10.1007/BF01797193>
- [2] Klem, G.H., Lüders, H.O., Jasper, H.H., Elger, C., The ten-twenty electrode system of the International Federation. *The International Federation of Clinical Neurophysiology. Electroencephalogr Clin Neurophysiol Suppl.* 1999;52:3-6. PMID: 10590970.
- [3] Compston, A. The Berger rhythm: potential changes from the occipital lobes in man, by E.D. Adrian and B.H.C. Matthews (From the Physiological Laboratory, Cambridge). *Brain* 1934; 57; 355-385. *Brain.* 133. 3-6. [10.1093/brain/awp324](https://doi.org/10.1093/brain/awp324).
- [4] Becker, R. O., G. Selden. *The body electric: Electromagnetism and the foundation of life.* Morrow, New York, 1985.
- [5] Petrov G. K., "Low-cost ECG system for nonhazardous use," 27th International Spring Seminar on Electronics Technology: Meeting the Challenges of Electronics Technology Progress, 2004., Bankya, Bulgaria, 2004, pp. 554-556 vol.3, doi: 10.1109/ISSE.2004.1490877.
- [6] Tzvetkov, P., Iliev, P., Petrov, G., "Low frequency data acquisition system for ECG – velo test applications", *Metrology and Metrology Assurance* 2003
- [7] Holtermann, B., Erhöhung der Kanalanzahl des Modular-EEG auf Mikrocontroller-Ebene. Diplomarbeit, Fachbereich Informatik, Fachhochschule Dortmund, 2008.
- [8] Webster J. G., "Medical Instrumentation Application and Design", Houghton-Mifflin 19924.
- [9] Mihova, P., Vinarova, J., Pendzhurov, I., Interactive methods of education in eHealth, First Armenian International Congress on Telemedicine and ehealth "Armtelemed: road to the future", Erevan, 14-16 October, 2011, ISBN 978-9939-67-046-1
- [10] Luis, L., Gomez-Gil, Jaime. (2012). Brain Computer Interfaces, a Review. *Sensors.* 12. 1211-1279. [10.3390/s120201211](https://doi.org/10.3390/s120201211).
- [11] Davis, K. Brain-Computer Interfaces: The Technology of Our Future. *UC Merced Undergraduate Research Journal.* 14. [10.5070/M414157331](https://doi.org/10.5070/M414157331).
- [12] Firth J., Errico P., "Low-Power, Low Voltage IC Choices for ECG System Requirements", *Analog Dialogue* 2.
- [13] Wurcer S., Moshe, "HOW TO Instrumentation Amplifiers", *Analog Devices*.
- [14] Smith, S. W., "The Scientist and Engineer's Guide to Digital Signal Processing", 1999 by California Technical Publishing
- [15] Kester, W. Designer's guide to instrumentation amplifiers. *Analog Devices*, 2006.
- [16] Gueulle, P., "Virtual instrumentation using PC", 1999 DMK Moscow
- [17] Kitchin, C., Avoiding op-amp instability problems in single-supply applications. *Analog Dialogue*, Volume 35, Number 1, 2001. Available at: <https://www.analog.com/en/resources/analogdialogue/article/s/avoiding-op-amp-instabilityproblems.html>
- [18] Dotsinsky, I., Stoyanov, T., Georgy, M. Power-line Interference Removal from High Sampled ECG Signals Using Modified Version of the Subtraction Procedure. *International Journal Bioautomation.* 24. 381-392. [10.7546/ijba.2020.24.4.000802](https://doi.org/10.7546/ijba.2020.24.4.000802).
- [19] Mihov, G., I. Dotsinsky, I., Georgieva, Ts. Subtraction procedure for powerline interference removing from ECG: improvement for non-multiple sampling. *Journal of Medical Engineering & Technology*, 29(5), pp. 238–243, 2005, DOI:10.1080/03091900412331280897.
- [20] Griffith, A., An Exploration of the OpenEEG Project, C.H.G. Wright's BioData Systems, Spring 2006, https://austingriffith.com/files/Griffith_OpenEEG.pdf

[21] Collins, T., Woolley, S., Nicholas, H., Haroon, L., Final-year Projects using Open Source OpenEEG. Computer Applications in Engineering Education. 24. 156–164. 10.1002/cae.21682.

[22] Mingkun, Huang, ChenXi, Hu, Bingqian Xu, Xiaoming Huang, Xiangming Gao, Zhao Ding, Shishang Guo, Wireless EEG monitoring system with wearable self-powered flexible sensors, Chemical Engineering Journal, Volume 519, 2025, 165446, ISSN 1385-8947, <https://doi.org/10.1016/j.cej.2025.165446>.

[23] Ivaylov, I. EEG classification for BCI using genetic algorithm and k-fold cross validation. Electrotechnica & Electronica (E+E), Vol. 56 (3-4), 2021, pp.38-45, ISSN: 0861-4717 (Print), 2603-5421 (Online).

[24] Dimitrov, A., Yankulova I., Khaosyt, E. D., v biologichni sistemi. Faber, Tarnovo, 2004, ISBN 954-775381-9 / 2004, ISBN 954775-381-9.

[25] Company-Bosch, Hartmann E., ECG front-end design is simplified with MicroConverter®. Analog Dialogue, Volume 37, Number 4, 2003. Available at: <https://www.analog.com/en/resources/analogdialogue/article/s/ecg-front-end-design-simplified.html>

[26] Zoltan, S. ECG recording, storing, filtering and recognition. CodeProject, 2010. Available at: <https://www.codeproject.com/Articles/55591/ECGrecording-storing-filtering-and-recognition>

[27] Huang, M., Hu, C., Xu, B., Huang, X., Gao, X., Ding, Z., Guo, S., Wireless EEG monitoring system with wearable self-powered flexible sensors. Chemical Engineering Journal, 2025. <https://doi.org/10.1016/j.cej.2025.165446>

[28] Nayak, C. S., Anilkumar, A. C., Normal EEG waveforms. In: StatPearls [Internet]. StatPearls Publishing, Treasure Island (FL), 2025. Available at: <https://www.ncbi.nlm.nih.gov/books/NBK539805/>

Vanessa S. Nazakova - has a bachelor degree in Telecommunications Engineering at New Bulgarian University, with research interests in brain-computer interfaces, bioelectrical signal processing. Hobbies include hiking and artistic endeavours.

tel.: +358 894 352 178 e-mail: v.nazakova@gmail.com

Received on: 30.04.2026