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Article in Przegląd Elektrotechniczny · February 2014
DOI: 10.12915/pe.2014.02.44

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Processing and spectral analysis of the raw EEG signal from the MindWave

Abstract. Electroencephalography (EEG) is commonly used in a variety scientific fields. Unfortunately, commercial devices are generally very expensive, costing thousands of dollars. In recent years, devices costing under \$200 have been made available. The MindWave MW001, developed by Neurosky Inc., is currently the least expensive commercial EEG device, costing less than \$100. The paper presents how to record and process the raw EEG signal from the MindWave MW001 in the MATLAB environment. This paper then show how Fast Fourier Transform (FFT) is used to find the frequency components in a time domain signal. Based on a sample signal and spectral analysis, the basic EEG waves are presented.

Streszczenie. Elektroencefalografia (EEG) jest powszechnie stosowana w wielu dziedzinach nauki. Niestety, urządzenia komercyjne są na ogół bardzo drogie, kosztują wiele tysięcy dolarów. W ostatnich latach, pojawiły się na rynku urządzenia kosztujące mniej niż 200\$. MindWave MW001 został opracowany przez firmę Neurosky i jest obecnie najtańszym komercyjnym urządzeniem EEG, kosztuje mniej niż 100\$. Artykuł przedstawia w jaki sposób można zapisać i przetwarzać surowy sygnał EEG w środowisku MATLAB przy użyciu urządzenia MindWave MW001. Następnie, szybka transformacja Fouriera jest zastosowana do znalezienia składowych częstotliwości badanego sygnału w dziedzinie czasu. Na podstawie próbek sygnału i analizy widmowej zaprezentowano podstawowe fale EEG. (Przetwarzanie i analiza widmowa sygnałów EEG przy zastosowaniu urządzenia MindWave MW001)

Keywords: electroencephalography, MindWave, spectral analysis, raw EEG signal.

Słowa kluczowe: elektroencefalografia, MindWave, analiza widmowa, surowy sygnał EEG.

doi:10.12915/pe.2014.02.44

Introduction

Electroencephalography (EEG) is the measurement of electrical activity in the living brain. The first electrical neural activities of the human brain were registered by Hans Berger (1924) using a simple galvanometer. On the human scalp was placed only one electrode, and one wave was identified. It was alpha wave (also called Berger's wave) [5]. Nowadays in clinical use of EEG, 21 electrodes are used to identified 5 fundamental waves, but this kind of the device costs thousands of dollars [12, 15, 17].

In recent years, inexpensive mobile EEG devices have been developed by Avatar EEG Solutions, Neurosky, OCZ Technology, InteraXon, PLX Devices and Emotiv Systems. These devices are not used in clinical use, but are used in the Brain Control Interface (BCI) and neurofeedback (one of biofeedback types). The BCI is a direct communication pathway between the brain and an external device [3, 4, 8, 9, 13].

The cheapest EEG device is single-channel MindWave MW001 produced by Neurosky Inc., San Jose, CA. It cost only around \$80. The device consists of eight main parts, ear clip, flexible ear arm, battery area, power switch, adjustable head band, sensor tip, sensor arm and inside thinkgear chipset. Figure 1 presents the device design.

The principle of operation is quite simple. Two dry sensors are used to detect and filter the EEG signals. The sensor tip detects electrical signals from the forehead of the brain. At the same time, the sensor pick up ambient noise generated by human muscle, computers, light bulbs, electrical sockets and other electrical devices. The second sensor, ear clip, is a grounds and reference, which allows thinkgear chip to filter out the electrical noise [16].

The device measures the raw signal, power spectrum (alpha, beta, delta, gamma, theta), attention level, mediation level and blink detection. The raw EEG data received at a rate of 512 Hz. Other measured values are made every second. Therefore, raw EEG data is a main source of information on EEG signals using MindWave MW001.

On the producer page, we can find more than 130 applications classified into 4 platforms, 5 genres and 16 developers. These apps do not provide the source code. Therefore, change of functionality is not possible. However,

dynamic-link library (thinkgear.dll) is available to handle the connection to the device.

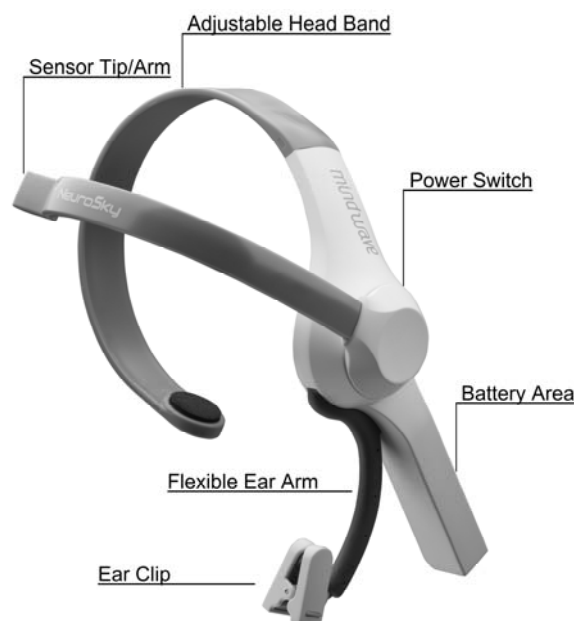


Fig. 1 The MindWave MW001 device design

The MATLAB allows to include thinkgear.dll. This environment has broad support in toolbox, which makes it ideal for a scientific research.

This paper presents how recording and processing the raw EEG signal in MATLAB environment using MindWave MW001. The rest of the paper is set out as follows: in section *The Communication Protocol*, the author presents a system of digital rules for message exchange between MATLAB environment and MindWave MW001 device. This section also presents the main parameters of thinkgear library. In section *Fast Fourier Transform* is presented an efficient algorithm to convert time domain of signal to frequency domain. This section, in brief, describes a mathematical base and MATLAB functions related with Fast Fourier Transform (FFT). Afterwards, in section

Experiments and Results, the author presents examples of recorded EEG signal in time and frequency domain. On the basis of signal samples and their spectral analysis, the basic EEG waves are presented. The conclusions are presented in the last section.

The Communications Protocol

The proposed communications protocol is a system of simple rules for message exchanges between MATLAB and the EEG device. It consists of 7 basic steps, which are presented in figure 2.

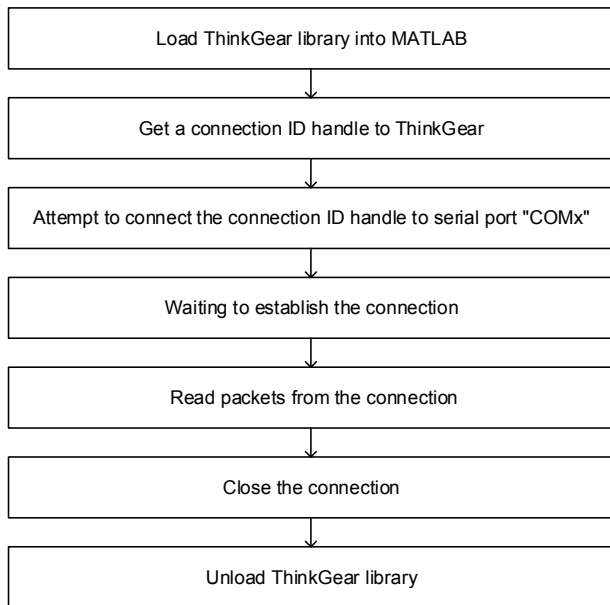


Fig. 2 The communications protocol

In the first step are functions with parameters in the following order::

1. *libisloaded('Thinkgear')* – returns true if the ThinkGear library is loaded, and false otherwise.
2. *loadlibrary('Thinkgear.dll','thinkgear.h')* – loads the functions defined in the header file and found in the library. Now, the function *calllib()* can call a function in the ThinkGear library.
3. *calllib('Thinkgear', 'TG_GetDriverVersion')* – returns the version of loaded library.

In the next step, the function *calllib('Thinkgear', 'TG_GetNewConnectionId')* gets a new connection ID handle to ThinkGear. The value -1 is returned if too many connections have been created.

In the ThinkGear library, the most important function is *TG_Connect*. This function needs 4 parameters: the connection ID, number of the serial port, Baud rate and type of data. The number of the serial port is given during the pairing of the device. The device can connect on modes 1200, 2400, 4800, 9600, 57600 and 115200 bits per second (bps). Additionally, we can use three formats of data streams: packets, 5V RAW and file packets. In this paper, the author uses the 9600 bps rate and stream 5V RAW mode, because these parameters have the minimum of transmission errors. The connection is established by using the following command:

```
calllib('Thinkgear', 'TG_Connect', Id, ComPortName,
TG_BAUD_115200, TG_STREAM_5VRAW)
```

In the next step, we must attempt to read a Packet of data from the connection. We use the *TG_ReadPackets()* function with ID parameter and number of packet to read.

The command *calllib('Thinkgear','TG_ReadPackets',Id,1)* returns false for error, and otherwise true. The function *TG_GetValueStatus()* checks if a value has been updated by *TG_ReadPackets()*. If this function returns true, we can use *TG_GetValue()* function to get the updated value of the raw EEG signal. Afterwards, we can read the value of raw EEG signal with the maximum frequency of 512 Hz. Sampling frequency is set on 512 Hz, and we control time delays in sampling. The value of the signal and time are written to the array *data*. A one-second sample of the EEG raw signal is presented in figure 3.

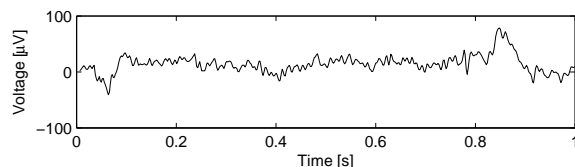


Fig. 3 One-second of a recorded sample of the raw EEG signal from the MindWave MW001.

Fourier Analysis

A Fourier series decomposes a periodic signal $x(t)$ in terms of an infinite sum of sines and cosines (or complex exponentials) [14, 6]. Mathematical formula of a Fourier series is presented by following formula (1):

$$(1) \quad x(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_n \cos(\omega kt) + b_n \sin(\omega kt)),$$

where signal $x(t)$ is integrable on an interval $[0, T]$ and is periodic with period T , t is a time variable, ω is an angular frequency and a_0 , a_n , b_n are Fourier coefficients. The expression, angular frequency, is presented as (2):

$$(2) \quad \omega = \frac{2\pi}{T}$$

The Fourier coefficient can be obtained by formulas (3-4):

$$(3) \quad a_n = \frac{2}{T} \int_0^T x(t) \cos(\omega kt) dt, \quad k = 0, 1, 2, 3, \dots, N,$$

$$(4) \quad b_n = \frac{2}{T} \int_0^T x(t) \sin(\omega kt) dt, \quad k = 1, 2, 3, \dots, N.$$

On the basis of Euler's formula (5):

$$(5) \quad e^{jt} = \cos t + j \sin t,$$

Fourier series can be also presented as (6):

$$(6) \quad x(t) = \sum_{k=-\infty}^{k=\infty} c_n \cdot e^{j\omega kt},$$

where coefficient c_n is obtained as (7):

$$(7) \quad c_n = \frac{1}{T} \int_0^T x(t) e^{-j\omega kt} dt.$$

A generalization of Fourier series, for infinite domains, is Continuous Fourier Transform (CFT). CFT is used to transform signals between time domain and frequency domain. The term CFT is presented as (8):

$$(8) \quad F(\xi) = \int_{-\infty}^{\infty} x(t) e^{-2\pi j \xi t} dt.$$

Then the inverse CFT (to transform signals between frequency domain and time domain) can be written as (9):

$$(9) \quad x(t) = \int_{-\infty}^{\infty} F(\xi) e^{2\pi j \xi t} d\xi.$$

If the signal is periodic, band-limited and sampled at Nyquist frequency or higher, the CFT is represented exactly

by Discrete Fourier Transform (DFT). DFT transforms the sequence of N complex numbers x_0, x_1, \dots, x_{N-1} (the time domain) into an N -periodic sequence $X_0, X_1, X_2, \dots, X_{N-1}$ (the list of coefficient of a finite combination of complex sinusoids, ordered by their frequencies). It is according to the DFT formula [10] (10):

$$(10) \quad X_k = \sum_{n=0}^{N-1} x_n e^{-j2\pi kn/N}.$$

Each X_k element encodes amplitude and phase of a sinusoidal component of function x_n . Inverse conversion to the DFT is the Inverse DFT (IDFT). The IDFT transforms data from the frequency domain to the time domain. It is according to the IDFT formula (11):

$$(11) \quad x_n = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N}.$$

In this paper, A Fast Fourier Transform (FFT) is used as efficient algorithm to compute the DFT and its inverse (IFFT to compute IDFT) [1, 2]. Computational complexity is $O(N^2)$ for standard DFT and $N(\log N)$ for FFT procedure. FFT algorithm is based on *Divide and Conquer* algorithm. It divides the transform of size N to transform the size N_1 and N_2 . In this paper, the FFT algorithm is using for size of sample, according formula (12):

$$(12) \quad N = 2^k,$$

where k is a natural number.

In MATLAB environment, the FFT and IFFT algorithms are implemented. Function `fft(data, N)` has two important input. *Data* is a vector of signal and N is a size of transform. If N is less than length of *Data*, the sequence x is truncated. If N is greater than length of *Data*, vector x is padded with trailing zeros to length N . This function returns the DFT of vector x , computed with the FFT algorithm. Function `ifft(Data, N)` works in the same way, but returns values from a time domain.

Experiments and Results

In this section, two samples of the raw EEG signal are investigated. On the basis of the proposed communications protocol, the samples by 400-second are recorded. The sampling frequency is defined as 512 Hz. Next, the signals are divided into 100 equal parts (each part - 4-second). Afterwards, for each signal one of the parts is selected as the representative of the signal, which has most similar spectrum to spectrum of the entire signal. Hereinafter, these two parts will be called the sample #1 and the sample #2.

The sample #1 is recorded during a reading of specialized text. It is a example of moderate intellectual effort case with open eyes (it can cause increasing the amount of ocular artifacts). In figure 4 the sample #1 in the time domain is presented. The values of voltage are in the range from -18 to 63 μV and the average value of the signal voltage is 14.8043 μV .

The sample #2 is recorded during a being in a state of relaxation. It was realized using a darkened room, closed eyes and relaxing music (no possible ocular artifacts in the signal). In figure 5 the sample #2 in the time domain is presented. The values of voltage are in the range from -31 to 48 μV and the average value of the signal voltage is 14.8043 μV .

General characteristics are near for both sample. The maximum amplitude of the signal is similar for both samples, but they are displaced relative to each other.

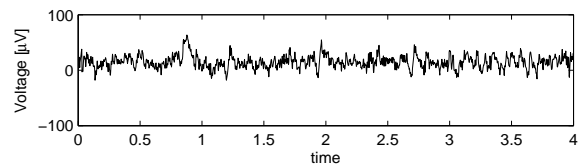


Fig. 4 The sample #1 of the raw EEG signal in the time domain.

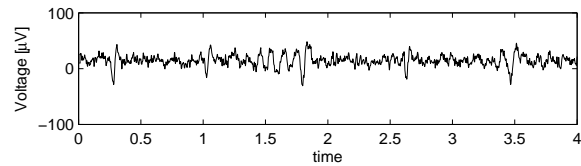


Fig. 5 The sample #2 of the raw EEG signal in the time domain.

The both signals are transformed from the time domain to frequency domain for spectral analysis [11]. The function `fft()` is obtained with the all values of sample and parameter (12) equal 2048. In the figure 6 and 7 the spectrums of frequency components are presented.

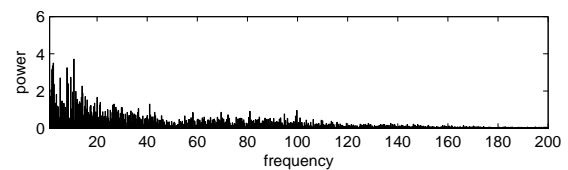


Fig. 6 The spectrum of frequency components for the sample #1.

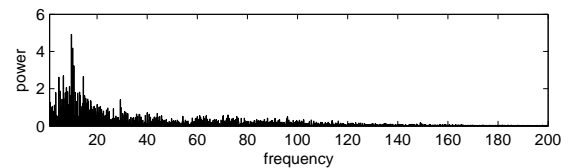


Fig. 7 The spectrum of frequency components for the sample #1.

The highest components of the signals have more power in the sample #1 than sample #2. This is caused by the presence of the gamma wave. It is defined as rhythms from 25 to 100 Hz, but commonly is used in the range from 40 to 80 Hz. The summary of the fundamental parameters of the basic brain waves is presented [12, 13] in table 1.

Tab 1. The summary of the basic human brain waves.

Name of the wave	Frequency [Hz]	Typical amplitude [μV]
Delta	0.1 – 4	100 – 200
Theta	4 – 8	higher than 30
Alpha	8 – 13	30 – 50 or higher
Beta	13 – 30	2 – 20 or higher
Gamma	40 – 80	3 – 5 or higher

The gamma waves can be implicated in creating the unity of conscious perception. It is supposed that this wave is responsible for the integration of different sensory modalities. To show the progress of this wave `ifft()` function is used, but before the all values of the components from outside of the range (40 – 80 Hz) are reset. In that way, the comparison of the gamma wave for the both samples are presented in figure 8 and 9. A higher activity of gamma wave in the sample #1 is observed. This is caused by a less strain on the brain in the sample #2.

If human is in a relaxed but aware state, the alpha waves are active [7]. Figure 10 and 11 are presented the alpha waves activity for the investigated samples. The higher activity of the alpha wave in sample #2 is observed. This is a consequence of the less mental activity for sample #2.

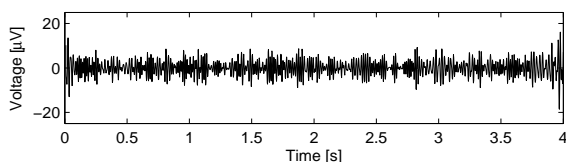


Fig. 8 The gamma wave for the sample #1 in the time domain.

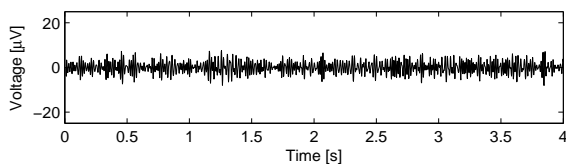


Fig. 9 The gamma wave for the sample #2 in the time domain.

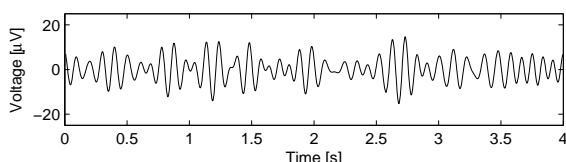


Fig. 10 The alpha wave for the sample #1 in the time domain.

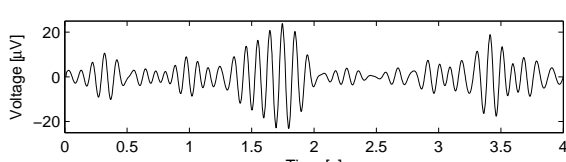


Fig. 11 The alpha wave for the sample #2 in the time domain.

The strongest brain activity is the delta wave. It is characterized by very low frequency up to 4 Hz and the amplitude higher than $100 \mu V$. The delta waves are usually associated with the deepest stages of sleep and aid in characterizing the depth of sleep. The both samples are rather weak in a comparison to the typical values of the amplitude. The variation of the delta waves is presented in figure 12 and 13.

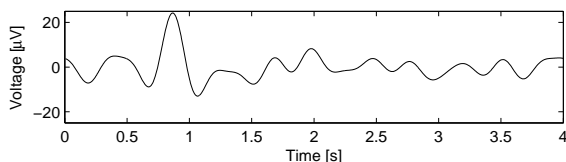


Fig. 12 The delta wave for the sample #1 in the time domain.

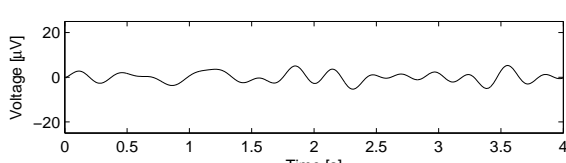


Fig. 13 The delta wave for the sample #2 in the time domain.

The theta waves are activated during a meditation, trance, hypnosis, intense dreams and intense emotions. In figure 14 and 15 the theta waves for the both samples are presented. The theta state is closer to relaxation state from sample #2. The difference is not large, but it is clear.

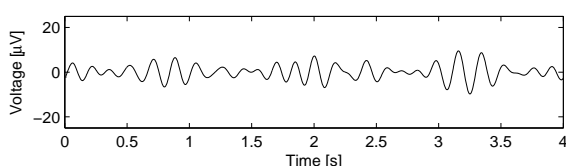


Fig. 14 The theta wave for the sample #1 in the time domain.

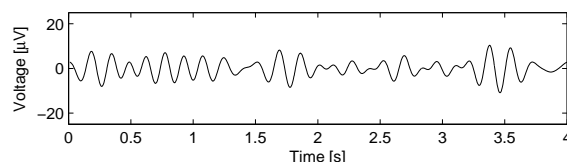


Fig. 15 The theta wave for the sample #2 in the time domain.

The last band of frequency of the spectral analysis, which will be analyzed, is called the beta waves. It responds of a human brain on the excited state. This may be due for example by a solving puzzles and other excited states. In the following experiment, it is the most similar pattern for the both samples. As it is showed in figure 16 and 17 the difference are very small, but for sample #1 the total power is a little higher, than in sample #2 (here we have only three strong spikes).

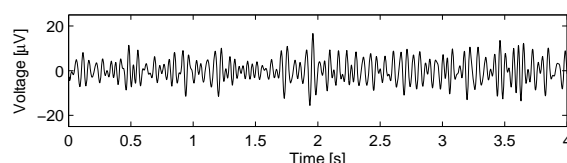


Fig. 16 The beta wave for the sample #1 in the time domain.

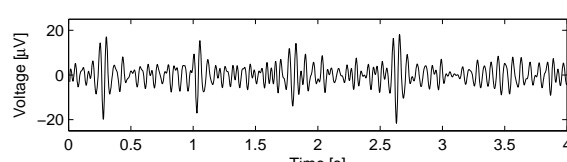


Fig. 17 The beta wave for the sample #2 in the time domain.

The proposed approach was presented and was verified as the result of the comparison between the different brain waves in two different cases (different states of mental). The all observations are consistent with the EEG theory. Naturally, the MindWave has a measurement error greater than the clinical devices, but it allows to made a basic study of the brain activity.

Conclusion

This paper present how to record and process the raw EEG signal from the MindWave MW001 in the MATLAB environment. For this purpose, the Fourier analysis has been used as an efficient way to make the spectral analysis. The first three section describe the theoretical assumptions. It is all used to perform the simple experiment. Two different mental state have been used to record and process the two samples of the raw EEG signal. On the basis of the spectral analysis the five kind of waves were identified. Afterwards, the samples were compared in respect of these waves. The observed differences are confirmed with theory knowledge.

In the result, the paper is presented the approach to efficient record and process the EEG signal with low financial outlay. This approach can be used for the neurofeedback and the brain control interface (BCI). The error of the device is too high for clinical use.

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