

Multi-target SSVEP-based BCI using Multichannel SSVEP Detection

Indar Sugiarto¹

¹*Department of Electrical Engineering, Petra Christian University
Jl. Siwalankerto 121-131, Surabaya, Indonesia*

¹indi@petra.ac.id

Abstract—Spatial filtering method and fast Fourier transform (FFT) based spectrum estimation method are applied to reveal the presence of steady state visual evoked potential (SSVEP) in multiple-electrodes electroencephalogram (EEG) signals used in Brain-Computer Interface (BCI) system. The SSVEP responses are elicited by visual stimuli in the form of flickering light emitting diode (LED) array and computer animation on the screen monitor. The essence of this method is to extract a narrowband frequency component of SSVEP in EEG. Subjects are instructed to shift their gaze during the trial to elicit multiple components of SSVEP spectrums. This approach which is called multi-target SSVEP is proposed to extend the feasibility of a BCI system. Using four subjects with two distinct stimuli, the experiment give a result of 41.6% accuracy for detecting dual-frequency combinations.

Index Terms—Brain-Computer Interface, steady state visual evoked potentials, electroencephalogram.

I. INTRODUCTION

SSVEP (Steady State Visual Evoked Potential) based BCI (Brain Computer Interface) is an example of successful application of brainwave acquisition and processing. One successful implementation of this technique is the Spelling Program Using SSVEP-based BCI [17]. In this spelling program, five flickering LEDs with distinctive frequencies are used to stimulate SSVEP.

The SSVEP has certain advantages for studying spatial attention in that it is rapidly quantifiable in the frequency domain and provides a continuous measure of the focusing and shifting of attention among items in a visual display. The SSVEP response is straightforward to model and characterize, and it is an inherent response of the brain, making the BCI system require no training for its subject. Fig 1 shows typical EEG signals and its spectral density when a subject receive visual stimulus with frequency of 7Hz.

Until now, the transfer rate in BCI system is very low compared to the common telecommunication system. The transfer rate up to 68 bits/min in nowadays BCI system perhaps can be considered as the highest, although some trials of certain BCI system may produce better result [3], [4]. One obvious opinion will rise then: if this rate could be increased, BCIs might offer all individuals useful ways to interact with their environment. To address this demand, a pilot project for increasing transfer rate of SSVEP-based BCI system has been proposed. If only the system can detect multiple frequency responses in the same time slot, then the transfer rate can also

be increased. Several researches have conducted and the published papers [5-8] show some promising possibilities for this purpose. In the proposed method, the subject should tow his/her attention on two different stimulators by shifting gaze. At the moment, the speed of this shifting gaze is not considered, but the effect of implementation of different stimulators will be observed.

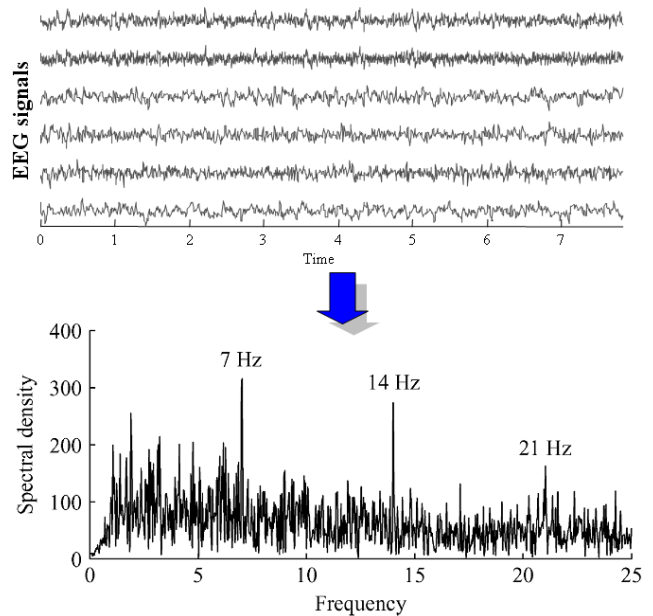


Fig 1. Typical SSVEP spectrums with a flickering frequency of 7 Hz. The harmonic frequencies are also produced at 14 and 21 Hz.

SSVEP signals have the strongest responses in the frequency range from 5 to 20 Hz [2]. It means that stimulator frequency modulates brain signals in alpha band and beta band. Naturally, BCI system will omit stimuli frequencies below 12 Hz because first harmonic responses from theta band will lay in the alpha band, making it difficult to distinguish them with original SSVEP response of alpha band [3], [8], [9]. Hence, the number of stimuli frequencies will be reduced, which in turn will alter the transfer rate of communication protocol of the BCI system. It is also natural to think about possibility to increase the transfer rate using only the available frequencies.

This paper will be presented in the following order. After giving an introduction, which explains the motivation of the research, the detail of the proposed multi-target SSVEP will be covered in section 2. Discussion about the implementation and experiment result will be given in section 3. This paper will be closed with discussion and conclusion in section 4.

II. METHOD

A. System Setup

In the BCI system used in this research, the brain signals are EEG signals that recorded from the scalp. Six electrodes as sensing elements were attached at locations P3, O1, PZ, OZ, P4, and O2 in the international 10-20 system, and referenced to a ground electrode placed at FZ, as described also in [2]. EEG paste was applied to bring impedances below 5 k Ω . An EEG amplifier from g.tec was used to acquire the electrode signals. An analog highpass filter with cutoff frequency 0.5 Hz was used in the amplifier, and the signals were digitized with a sampling rate of 128 kHz. The following diagram shows the system setup used in this research.

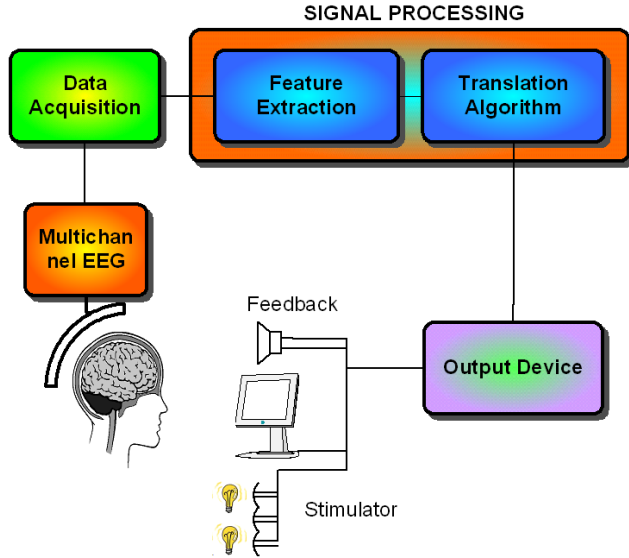


Fig 2. System setup used in the research.

After the signal is acquired and digitized, it is then subjected to the signal-processing element of the BCI system. The first component of this signal-processing element is feature extraction component, which extracts feature information from the input signals like the frequency of the signal and its corresponding harmonics.

The next step of signal processing element is the translation algorithm, which translates the signal features into device commands that carry out the user's intent. In the SSVEP-based BCI, the detected frequencies in the feature extraction part can be used to actuate output devices. These output devices are selected based on the purpose and required application of the BCI system. Many BCI systems used

nowadays are still in research level. That is why the computer screen becomes common as an output device for such BCI systems.

In the system setup as shown in Fig 2, well-defined light stimuli are used for stimulating the visual system, either by using LED (Light Emitting Diodes) array or by using animation on the monitor screen. These stimuli elicit responses in the visual cortex, which are acquired as visually evoked potentials (VEP) by a suitable system of electrodes. Depending on the stimulation frequency, a distinction is made between transient VEP (TVEP) and steady state VEP (SSVEP). Transient VEP arises if the electrical excitations of the visual system are able to abate before new stimuli are presented. If the repetition rate of stimuli is faster than 6/s, responses begin to merge and the shape of the resulting SSVEP becomes periodic [10]. The detection problem then is reduced to find this periodic component. When attention is directed towards a particular location in the visual fields, stimuli presented at that location typically elicit enlarged potential in relation to stimuli at unattended locations.

B. Multiple Electrodes Approach

A wide range of approaches to the detection of SSVEP has been proposed based on frequency-domain analysis or time-domain analysis. These also include statistical method [10], [11], adaptive matched filtering [12], and time-frequency analysis [13].

One way to improve SSVEP detection is by using multiple electrodes in an EEG recording. One reason for using this multiple electrodes is that it is beneficial to exploit the information in multiple electrode signals [2], [15], [17]. It is also known that the SSVEP response is widely distributed over the occipital and parietal lobes and the SSVEP responses on the same locations may differ from one subject to another. To extract the SSVEP response over multiple electrodes, we propose using spatial filtering method. The method is mainly based on minimum energy combination as proposed by [2]. The idea is to form combinations of the electrode signals that cancel as much of the nuisance signals as possible. To achieve this, the first step is to remove any potential SSVEP components from all the electrode signals, which is done by projecting them onto the orthogonal complement of the SSVEP model matrix X described as:

$$X = [X_1 X_2 X_3 \dots X_N] \quad (1)$$

where each submatrix X_k contains a $\sin(2\pi fkt)$ and $\cos(2\pi fkt)$ pair in its columns.

Assuming that visual stimulation with a flicker-frequency of f Hz is applied, the model for signal $y_i(t)$ measured as the voltage between a reference electrode and electrode number i is:

$$y_i(t) = \sum_{k=1}^{N_k} a_{i,k} \sin(2\pi fkt + \phi_{i,k}) + \sum_j b_{i,j} z_j(t) + e_i(t) \quad (2)$$

Alternatively, in matrix form:

$$Y = AX + ZB + E \quad (3)$$

where $\mathbf{Y} = [y_1, \dots, y_{N_y}]$ is a $N_t \times N_y$ matrix with sampled signals from all electrodes as columns, \mathbf{Z} is a matrix with the nuisance signals in its columns, \mathbf{E} is the noise matrix, \mathbf{A} and \mathbf{B} contain the amplitude and scaling factors for all sinusoids and nuisance signals. Since the model is linear, it is natural to create a channel signal by combining the original electrode signals linearly using a $N_y \times 1$ vector of weights \mathbf{w} . A channel s is then obtained as

$$\mathbf{s} = \sum_{i=1}^{N_y} w_i y_i = \mathbf{Y}\mathbf{w}, \text{ or in matrix form, } \mathbf{S} = \mathbf{Y}\mathbf{W} \quad (4)$$

Since the SSVEP response is periodic signal with energy only in a few distinct frequencies, a test statistic for testing the presence of an SSVEP response can be calculated as:

$$T = \frac{1}{N_s N_h} \sum_{l=1}^{N_s} \sum_{k=1}^{N_h} \frac{P_{k,l}}{\sigma_{k,l}^2} \quad (5)$$

Here, $P_{k,l}$ is the estimated power in SSVEP harmonic frequency number k in channel signal sl , and $\sigma_{k,l}^2$ is an estimate of the noise power in the same frequency.

$$P_{k,l} = \| \mathbf{X}_k^T \mathbf{s}_l \|^2 \quad (6)$$

$$\sigma_{k,l}^2 = \frac{\pi N_t}{4} \frac{\sigma^2}{\left| 1 + \sum_{j=1}^p \alpha_j \exp(-2\pi i j k f / F_s) \right|^2} \quad (7)$$

The idea for calculating noise power is to fit autoregressive AR(p) models to the channel signals, and use the fitted models to interpolate the noise power in the SSVEP frequencies. The AR(p) models are efficiently fitted by invoking the Wiener-Khinchin theorem for computing the autocovariance of each channel signal and then solving the Yule-Walker equations using a Levinson-Durbin recursion. This yields the AR(p) model parameters $\alpha_1, \dots, \alpha_p$, as well as an estimate of the variance σ^2 of the white noise driving the AR(p) process. Using the test statistic, or SNRs, described above, the SSVEP response for certain frequencies can be detected.

C. Multiple Electrodes Approach

Müller et al. have observed that it is possible to gain SSVEP responses when stimuli are presented in the same hemifield although the experiment results showed that task performance was in general lower opposed to the same task with different hemifield presentation [5-7]. The possibility to attend spatially separate locations within as well as across visual hemifields has opened another possibility that is multi-target SSVEP detection.

Another research conducted by Srihari Mukesh et al. also try to improve the self-made BCI instruments by exploring the method to increase the number of BCI commands by using a suitable combination of frequencies for

stimulation [8]. With their efforts, they were able to make six selections (commands) by generating only three frequencies.

In this research, multi-target SSVEP is performed by focusing on two LED arrays or two animations on the monitor screen at the same time. Here is the proposed experiment protocol:

1. Subject sits in front of stimulator and takes the distance where the subject feels comfortable enough with his/her position.
2. EEG signals will be recorded for 10 seconds when subject attends the following flickering frequencies: 13 Hz, 14 Hz, 15 Hz, 16 Hz, 17 Hz, 13 and 14 Hz, 13 and 15 Hz, 13 and 16 Hz, 13 and 17 Hz, 14 and 15 Hz, 15 and 16 Hz, 15 and 17 Hz.
3. When subject directs his/her attention to two flickering frequencies, he/she may shift the gaze at arbitrary speed at which the subject feels comfortable.
4. A short break could be taken by the subject when the experiment finishes with one frequency measurement and ready to advance to the next frequency.

III. EXPERIMENT RESULT

After EEG signals had been recorded from four subjects, the collected data then being processed using the proposed method. We also used FFT (fast Fourier transform) to obtain frequency spectrum in Matlab for exploring possibilities of two simultaneous frequency occurrences.

For the first subject, we used real LED stimulator to elicit SSVEP response. From this subject, multiple SSVEP spectra were detected, especially for frequency combination of 13-16 Hz, 13-17 Hz, 15-16 Hz, and 15-17 Hz. In those frequency combinations, spikes are found although spikes of nuisance signals are also present. This spike from noise can be removed by filtering only if characteristic of this noise is known in advance. The following graph shows the SSVEP response for stimuli with frequency combination of 13-16 Hz.

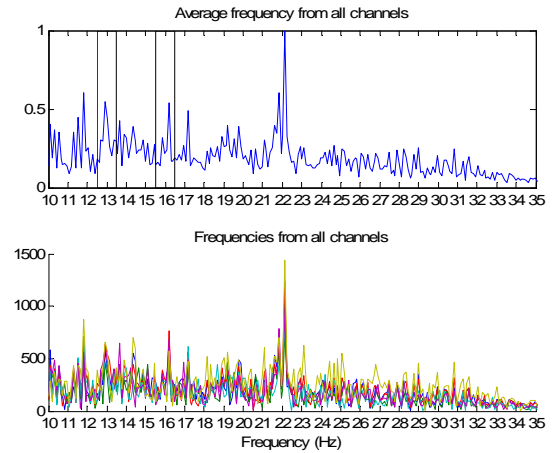


Fig 3. SSVEP response of subject number one for stimuli with frequency combination of 13-16 Hz.

Unfortunately, for the subject number two, we did not see much from the frequency spectrum analysis. Although there is a spike in the corresponding stimulator frequencies, we also see spikes in unrelated frequencies. In the frequency combination from 13-14 Hz to 13-17 Hz, it is easier to detect the 13 Hz but not for its pair. The same phenomenon also happens to the frequency pair 14-15 Hz. Only in the frequency combination 15-16 Hz and 15-17 Hz, we see equivalent level of considerable spikes.

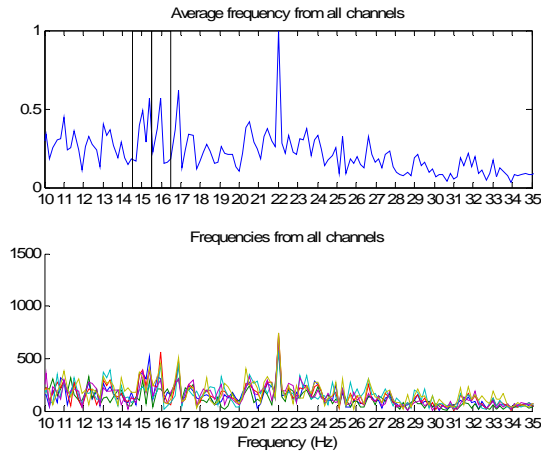


Fig 4. SSVEP response of subject number two for stimuli with frequency combination of 15-16 Hz.

For subject number three, we saw good responses in the frequency combination of 13-14 Hz, 13-16 Hz, and 13-17 Hz, while in the other frequency combination, one frequency is dominant than its pair.

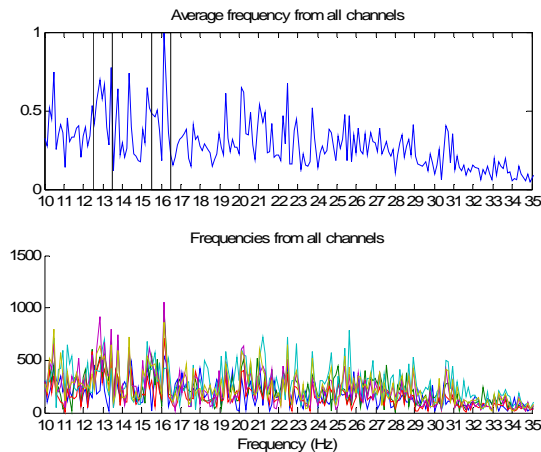


Fig 5. SSVEP response of subject number three for stimuli with frequency combination of 13-16 Hz.

For subject number four, the only considerably good frequency pair is 13-15 Hz. While there are quite high spikes in frequency pair 14-15 Hz, it is unclear whether these spikes really elicited by the stimulator at those frequencies since these spikes lay in the middle of two frequencies. In the other

frequency pairs, we do not see any significant correlation with its stimulator frequency.

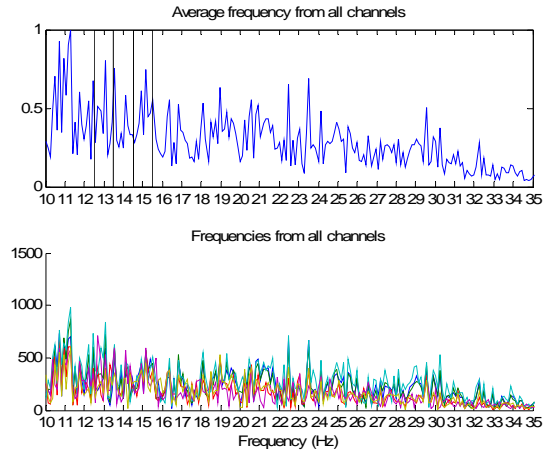


Fig 6. SSVEP response of subject number four for stimuli with frequency combination of 13-15 Hz.

To summarize, the following table combines information from the previous analysis. The parameter key to justify these frequency pairs is by comparing with another frequency part and use band-pass filter to limit the frequency band only in the range from 13 Hz to 17 Hz. We enhanced the observed frequencies by applying filter and normalization. We define it as good if both frequencies have significant amplitude and distinguishable from the other frequencies. We define it as fair if both frequencies show tendency to become spike although their amplitude is not higher than the other frequencies. We define it as unclear if the frequency pair is unbalance (one frequency pair is much higher than its counterpart) or when those frequencies are too small compared with the other frequencies.

TABLE I
DETECTION OF MULTI-FREQUENCY IN SSVEP RESPONSES.

Stimulator Frequencies (Hz)	Subject one	Subject two	Subject three	Subject four
13-14	Unclear	Unclear	Fair	Unclear
13-15	Unclear	Unclear	Unclear	Good
13-16	Good	Unclear	Good	Unclear
13-17	Fair	Unclear	Fair	Unclear
14-15	Unclear	Unclear	Unclear	Unclear
15-16	Good	Unclear	Good	Unclear
15-17	Fair	Fair	Unclear	Unclear

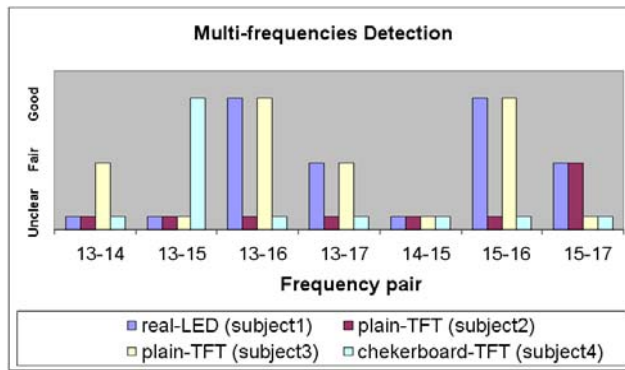


Fig7. Detection result for multi-target SSVEP.

After calculation, we found that 41.6% of frequency combinations were able to be detected using the proposed method.

IV. DISCUSSION AND CONCLUSION

There is a difference of waveform of light intensity radiated by the monitor when the animation switched from simple plain black-and-white pattern to checkerboard pattern. This difference may affect the SSVEP response since from evaluation we found that simple plain texture gives better response in SSVEP than the checkerboard pattern.

When observing SSVEP signals to detect two simultaneous frequencies, it is difficult to utilize the minimum energy filter. However, frequency spectrum analysis reveals this possibility. It is possible to apply filtering and normalization to enhance the frequency pair and continue with threshold operation to determine whether the investigated frequency pair can be considered detected or not. These operations must be applied to all frequencies and frequency pairs in the same time (parallel processing). Although this method is technically possible, but the running cost of this approach may be high. Another challenge is to combine the frequency domain filtering method with the proposed spatiotemporal filtering method.

At this time, it is unclear whether the two frequencies approach with gaze shifting method is superior. Additional work in the full study of this approach should include gaze shifting observation, different frequencies, different display parameters, distance between targets, and improved signal processing.

ACKNOWLEDGMENT

The authors would like to thank Dr. Brendan Allison, Dr. Bernhard Graimann and Prof. Axel Gräser from Institute for

Automation at University of Bremen for their advice, and all volunteers for taking part in the experiment.

REFERENCES

- [1] J. Wolpaw, N. Birbaumer, D. McFarland, G. Pfurtscheller, T. Vaughan. "Brain-computer interfaces for communication and control". *Clinical Neurophysiology* 113 (2002) 767 – 791.
- [2] O. Friman, I. Volosyak, A. Gräser. "Multiple Channel Detection of Steady-State Visual Evoked Potentials for Brain-Computer Interfaces". *IEEE Transaction On Biomedical Engineering*, Vol. 54, No. 4, April 2007.
- [3] M. Cheng, X. Gao, S. Gai. "Design and Implementation of a Brain-Computer Interface With High Transfer Rates". *IEEE Transaction On Biomedical Engineering*, Vol. 49, No. 10, October 2002.
- [4] X. Gao, D. Xu, M. Cheng, and S. Gao. "A BCI-Based Environmental Controller for The Motion-disabled". *IEEE Transaction On Neural System Rehabilitation Engineering*, Vol. 11, No. 2, June 2003.
- [5] M. Müller, T. Picton, P. Valdes-Sosa, J. Riera, W. Teder-Sälejärvi, S. Hillyard. "Effects of Spatial Selective Attention On the Steady-state Visual Evoked Potential in the 20-28 Hz Range". *Cognitive Brain Research* 6 (1998) 249 – 261.
- [6] M. Müller, P. Malinowski, T. Gruber, S. Hillyard. "Sustained Division of The Attentional Spotlight". *Letters to Nature* Vol. 424, July 2003.
- [7] P. Malinowski, S. Fuchs, M. Müller. "Sustained Division of Spatial Attention to Multiple Locations Within One Hemifield". *Neuroscience Letters* 414 (2007) 65-70.
- [8] T. Mukesh, V. Jaganathan, M. Reddy. "A Novel Multiple Frequency Stimulation Method for Steady State VEP Based Brain Computer Interface". *Physiological Measurement* Vol. 27 (2006), 61-71.
- [9] Y. Wang, R. Wang, X. Gao, B. Hong, S. Gao. "A Practical VEP-Based Brain-Computer Interface". *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 14, No. 2, June 2006.
- [10] A. Liavas, G. Moustakides, G. Henning, E. Psarakis, P. Husar. "A Periodogram-Based Method for the Detection of Steady-State Visually Evoked Potentials". *IEEE Transaction On Biomedical Engineering*, Vol 45, No. 2, February 1998.
- [11] Z. Lin, C. Zhang, W. Wu, X. Gao. "Frequency Recognition Based on Canonical Correlation Analysis for SSVEP-Based BCI". *IEEE Transaction on Biomedical Engineering*, Vol. 53, No. 12, December 2006.
- [12] C. Davila, R. Srebo, I. Ghaleb. "Objective Measurement of Visual Contrast Sensitivity via Adaptive Matched Filtering of Steady-State VEP's". *Proceeding of IEEE Engineering in Medicine and Biology*, 1995.
- [13] G. Henning, O. Hoenecke, P. Husar, K. Schellhorn, U. Trautwein. "Time-frequency Analysis of Flicker-Burst Visual Evoked Responses". *Proceeding of IEEE Engineering in Medicine and Biology*, 1995.
- [14] J. Wolpaw, D. McFarland. "Multichannel EEG-based brain-computer communication". *Electroencephalogram Clinical Neurophysiology* Vol. 90, no.6, 1994.
- [15] B. Peters, G. Pfurtscheller, H. Flyvbjerg. "Mining multi-channel EEG for its information content: an ANN-based method for a brain-computer interface". *Neural Network* Vol. 11, no.7-8, 1998.
- [16] G. Burkitt, R. Silberstein, P. Cadush, A. Wood. "Steady-state Visual Evoked Potentials and Travelling Waves". *Clinical Neurophysiology*, Vol 111, No. 2, 246-258, 2000.
- [17] Ola Friman, Thorsten Lüth, Ivan Volosyak and Axel Gräser. "Spelling with Steady-State Visual Evoked Potentials". *Proceedings on 3rd International IEEE EMBS Conference on Neural Engineering - NER*, 2007