A Fractal Dimension Based Algorithm for Neurofeedback Games

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***Abstract*—Neurofeedback systems attracted more attention recently from the research community and industry as wireless EEG reading devices became easily available on the market. New application areas include medical applications such as pain management, sleep disorder, depression treatment, etc., non-medical applications as well such as e-learning, entertainment, etc. Neurofeedback games involve multi-disciplinary researches including signal processing algorithms, 2D or 3D game development, and research on medical application domains. In this paper, we study fractal dimension model and propose an adaptive algorithm of brain state recognition in neurofeedback games. Our hypothesis is that changes in the brain state can be noticed as changes in fractal dimension value. The fractal dimension is calculated by Higuchi algorithm and defines the current state of the brain. The adaptive neurofeedback algorithm threshold value is calculated. We also proposed and developed a new game "Brain Chi" that allows the user to play the game by concentration. By using so-called "brain power", the player could get the points rewards when fighting bat enemies. The "brain power" is visualized as "growing/shrinking" ball. The game could be used for entertainment and attention enhancement. Medical application domains would be studied in the future.**

Keywords-HCI, neurofeedback games, EEG, fractal dimension, BCI

I. INTRODUCTION

Traditionally, EEG-based technology has been applied in medical applications. Human electroencephalograph (EEG) signals are the records of electrical potential produced by the brain along with its activities. EEG signals are analyzed to understand how the brain works, and the analysis results are used in the diagnosis and treatment of different diseases such as Alzheimer, epilepsy, cognitive disorders, etc. Another important application of EEG-based technology is research and development of non-invasive Brain-Computer Interfaces (BCI) that allow directly to manipulate information on the computer in real time [1]. Neurofeedback systems were used in medical therapy for a long time [2]. Both non-invasive BCIs and neurofeedback systems are based on the real-time analysis of EEG signals. Neurofeedback is a process of displaying involuntary physiological processes as EEG analysis visual interpretation, and then, learning to voluntarily influence those processes observing visually the change. Neurofeedback, as a therapy, treats health problems like, attention deficit disorders, hyperactivity disorders and sleeping problems instead of suppressing such diseases with medication [3]. Based on visual feedback showing the user's brain activity, the user's mind could be trained to either increase or decrease specific brain functions. Intensive colors, game characters, or other visual effects can be used as visual feedback to the user.

Now, 2D and 3D graphics with virtual reality enhancement are more used in neurofeedback games [4-5]. The signal is usually processed and analyzed from real-time EEG readings in frequency domain. It could be also processed with signal processing algorithms (noise reduction, filtering and other processing), and the resulting values can be fed back to the system, and depending on the game scenario, could be interpreted, for example, as an avatar walking or driving through in 2D-3D environments [1], or changing of objects colors or sizes, etc. Most of the methods used in neurofeedback systems are based on linear analysis. But the nature of EEG signal is not linear. Thus, recently, more researchers started to study and apply chaos theory based algorithms using fractal dimension values for the EEG signal classification [6-11]. Fractal dimension model can be used to analyze the complexity of time-series signal and capture the changes of the signal geometry. Although the fractal model is used in EEG classification algorithms, there is very few preliminary works studying fractal dimension model application in neurofeedback games [12].

Neurofeedback games usually require the doctor assistance. There is a demand for the games that could be used for training at home. An integration of the EEG analysis algorithms and 2D-3D game development is the most recent R&D direction in medical and non-medical applications. In this paper, we proposed and implemented the neurofeedback algorithm based on fractal dimension model. Our assumption is that changes in the brain state can be noticed as changes in fractal dimension. Then, the change in the fractal dimension value could be input into the game and interpreted as the change of colors, game characters appearance, or other visual effects that are used as visual feedback to the player. The user could train specific brain function depending on the electrode/electrodes placement. In our study, we activated one electrode, processed the corresponding signal with well-known fractal dimension algorithm, and calculated the adaptive threshold for the game control. An occipital lobe electrode placement was chosen in our experiments as the increased activity in occipital lobe with sustained attention was reported in works [13-14]. We developed a new game "Brain Chi" that could be used in entertainment and has a great potential in medical applications such as pain management, attention enhancement, etc.

In Section 2, a fractal dimension model and algorithms are briefly described. The experiment analysis is also shown. In Section 3.1, the proposed adaptive neurofeedback algorithm is given. The implemented game is described in Section 3.2. Section 4 discusses conclusion and possible medical applications.

II. Fractal Dimension Algorithms and Analysis

A. *Fractal dimension model and algorithms*

Fractal dimension (FD) algorithms are used for EEG signal processing in many applications such as diagnosis of Alzheimer's disease, schizophrenia, etc [9, 15]. There are many fractal dimensions and the corresponding algorithms that are used in different applications. In this paper, we consider Hausdorff dimension and study well-known Higuchi and box-counting algorithms for the real-time brain state recognition. Fractal dimension is a measurement of complexity [16]. The changes of the signals which are self-similar or have fractal nature, such as EEG signals, can be noticed by the changes of fractal dimension values. The complexity of EEG signals has strong relationship with the activity of the brain. Monitoring the changes in EEG signal could reveal the changes in the brain state.

In order to calculate the fractal dimension of EEG signals, two algorithms were compared in our study. In Higuchi algorithm[17], k-dimension phase space is reconstructed by embedding time-delay information, i.e. construct poly-phase subsequences from the recording signals as equation (1):

$$X_k^m : x(m), x(m+k), x(m+2k), ..., x\left(m + \mathrm{int}\left[(N-m)/k\right]k\right) \quad (1)$$

where, m donates the m-th subsequence, and N is the total number of samples of the original sequence. The capacity number occupying the space was calculated according the length over the m-th subsequences $L_m(k)$ as equation (2):

$$L_m(k) = \frac{1}{k}\left[\left(\sum_{i=1}^{\mathrm{int}(N-m/k)} | x(m+ik) - x(m+(i-1)k) |\right) \frac{N-1}{\mathrm{int}((N-m)/k)k}\right] \quad (2)$$

The total length $L(k)$ is proportional to k^{-FD} as equation (4):

$$L(k) = \sum_{m=1}^{k} L_m(k)/k \quad (3)$$

$$L(k) \propto k^{-FD} \quad (4)$$

Fractal dimension value can be calculated by the least-square linear best fitting line procedure over the graph $\left(\ln(1/k), \ln(L(k))\right)$.

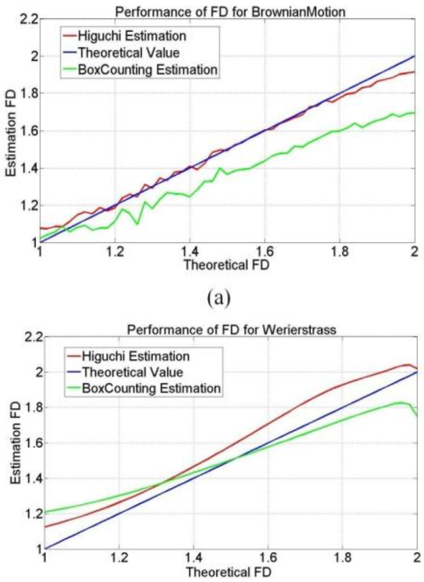
In box-counting method, the fractal dimension value is evaluated from the time-amplitude space directly by counting the normalized boxes occupied by the signals [18]. The number of counting boxes N(d) is proportional to d^{-FD}, where d donates the radii of the boxes:

$$N(d) \propto d^{-FD} \quad (5)$$

The best line fitting method was also used to calculate the fractal dimension value after counting the boxes.

B. *Experiment and fractal dimension analysis*

First, the comparison between the Higuchi method and Box-counting method was done on monofractal Weierstrass and Brownian motion signals[19] for which the theoretical FD values are known in advance. Higuchi algorithm can achieve a better evaluation of the FD value comparing to the Box-counting method as seen in Figure 1. However, the Higuchi algorithm needs more time and requires higher sampling frequency due to the complicated poly-phase extraction. The algorithm complexity of Higuchi method is $O(N^2)$ comparing to the $O(N)$ of the box-counting method.



(a)

(b)

Figure 1. The comparison of Higuchi and Box-counting algorithms for FD evaluation over (a) Brownian Motion signals and (b) Weierstrass signals.

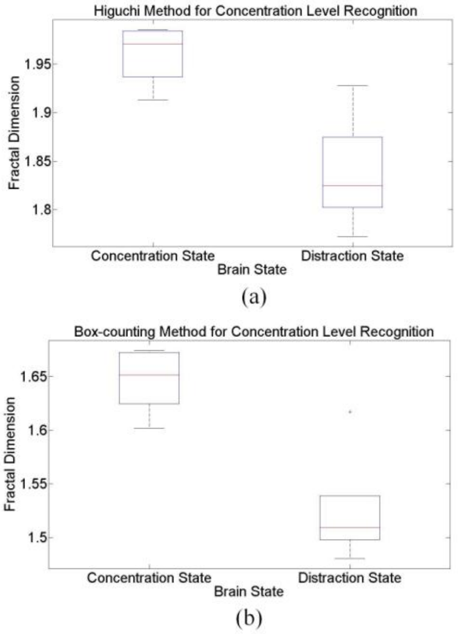


Figure 2. The comparison of (a) Higuchi method and (b) Box-counting method in FD evaluation of the EEG signals in different brain states for all subjects.

Second, the experiment was conducted to compare the results of FD values of EEG signals when the subjects were concentrating on solving simple mathematical problems, and when the subjects were distracted by more than one stimulus. The experiment was done with 5 subjects. The recognized brain states correspond to the states we recognize in our neurofeedback game. The electrode was placed in the O1 position (occipital lobe) according to the 10-20 international system[20] with Emotiv device. The results of the experiment are shown in Figure 2 by box plots. In both Higuchi and Box-counting algorithms, the experiment results show that concentration level can be distinguished for 80% subjects. The default threshold was set to 1.9 in Higuchi method and 1.55 in Box-counting method. For 100% subjects, the concentration level can be recognized with a trained threshold.

III. EEG-BASED GAME

A. Neurofeedback game algorithm

In our neurofeedback system, the Emotiv device records 128 EEG samples per second with 16-bit resolution for every channel. The electrode was placed in the O1 position according to the 10-20 international system as the occipital lobe has increased activity with sustained attention [13-14] , and "eye blinking" would not interfere with FD calculation.

In Figure 3, the overall neurofeedback algorithm is shown. Raw data is acquired from the headset using Emotiv Development kit. Then, the data is processed by Higuchi algorithm to evaluate the fractal dimension value of EEG signal in real-time.

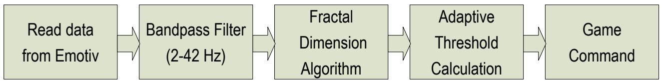


Figure 3. The game algorithm diagram.

The window size is set to 1024 points with approximately 99% overlap rate in the dynamic fractal dimension model. The real-time fractal dimension value is interpreted as the attention level of the brain, and a command for the game control is calculated according to the threshold value. In Section 2, the default threshold was calculated as 1.9 with Higuchi algorithm. For a new user, a threshold could be calculated in 20s training session. The threshold could be recalculated depending on the user's progress in training to increasing the fractal dimension value.

B. Game "Brain Chi" Setup and Description

This game "Brain Chi" aims to provide entertainment and sustained attention training for kids and adults. Game's hardware includes Emotiv headset [21]. EEG signal is transmitted via wireless communication which is enabled by a USB device along with Emotiv Kit (Shown in Figure 4). PET 2.0 device can be used as well [22]. The neurofeedback algorithm and 2D game was implemented in C++ language and SDL library [23].

"Brain Chi" game is designed for a single-player and can be controlled solely with the player's "brain power". The avatar in the game is a little boy who fights against evil bats. In Figure 5, the screenshot of the game and the game setting with Emotiv device are shown. The player uses his/her concentration to control the size of the protective ball. The aim of the game is to increase the ball to stop the bats from coming closer and kill all the bats to win.

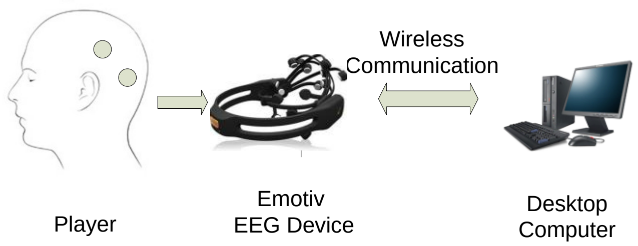


Figure 4. Hardware setup of the game

(a)

(b)

Figure 5. (a) Screenshot of the game and (b) game setting

IV. Conclusion and Future Work

In this paper, we studied fractal dimension model and well-known algorithms Box-Counting and Higuchi algorithms, then, we proposed and implemented the adaptive neurofeedback algorithm based on the Higuchi method. Both methods show the ability to detect different concentration levels of the brain and could be adopted in neurofeedback games. We proposed and implemented the original neurofeedback 2D game “Brain Chi” that could be used for entertainment. We are planning to study medical application domains and to carry out experiments for a pain management application. Preliminary study showed a great potential of our research for the pain management. We are planning to propose and develop series of games “Brain Chi” for treatment and even prevention of different medical conditions. Depending on the electrode/electrodes placement, we expect that different parts of the brain could be trained with our adaptive neurofeedback algorithm in future. The result of our research would contribute to the new forms of human-computer interaction (HCI) leading to the next generation of interactive media. Now, new affordable electro-encephalograph cap devices with wireless data transmission are entering the market that could encourage wide spread of new applications , e.g. bring the concentration-based and even emotion-based personalized digital experience to any user’s location and making such applications more mobile. In such interfaces, the content could be driven by monitoring of emotions and level of engagement/concentration, and, depending on the application (entertainment, learning, medical application, etc), different software tools should be engaged in real time. A short video about the implemented game presented in this paper can be seen at the following website.

http://www3.ntu.edu.sg/home/EOSourina/

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References

[1] Lécuyer, A., et al., *Brain-computer interfaces, virtual reality, and videogames.* Computer, 2008. 41(10): p. 66-72.

[2] Evans, J.R. and A. Abarbnanel, *An introduction to quantitative EEG and Neurofeedback*. 1999, San Diego: Academic Press.

[3] Holtmann, M., et al., *Neurofeedback for the treatment of attention-deficit/hyperactivity disorder (ADHD) in childhood and adolescence.* Zeitschrift Fur Kinder-Und Jugendpsychiatrie Und Psychotherapie, 2004. 32(3): p. 187-200.

[4] Cho, B.H., et al., Neurofeedback training with virtual reality for inattention and impulsiveness. Cyberpsychology & Behavior, 2004. 7(5): p. 519-526.

[5] Shim, B.S., S.W. Lee, and J.H. Shin, Implementation of a 3-Dimensional Game for developing balanced Brain-wave, in SERA 2007: 5th ACIS International Conference on Software Engineering Research, Management, and Applications, Proceedings, H.K. Kim, et al., Editors. 2007. p. 751-758.

[6] Kulish, V., A. Sourin, and O. Sourina, *Analysis and visualization of human electroencephalograms seen as fractal time series.* Journal of Mechanics in Medicine and Biology, 2006. 6(2): p. 175-188.

[7] Kulish, V., A. Sourin, and O. Sourina, *Human electroencephalograms seen as fractal time series: Mathematical analysis and visualization.* Computers in Biology and Medicine, 2006. 36(3): p. 291-302.

[8] Phothisonothai, M. and M. Nakagawa, EEG-based classification of motor imagery tasks using fractal dimension and neural network for brain-computer interface. IEICE Transactions on Information and Systems, 2008. E91D(1): p. 44-53.

[9] Sabeti, M., et al., *Selection of relevant features for EEG signal classification of schizophrenic patients.* Biomedical Signal Processing and Control, 2007. 2(2): p. 122-134.

[10] Sourina, O., A. Sourin, and V. Kulish. EEG Data Driven Animation and Its Application. in Computer Vision/Computer Graphics Collaboration Techniques, Proceedings. 2009.

[11] Sourina, O., V.V. Kulish, and A. Sourin. Novel Tools for Quantification of Brain Responses to Music Stimuli. in 13th International Conference on Biomedical Engineering,Proceedings. 2009. New York: Springer.

[12] Bashashati, A., et al. Fractal dimension-based EEG biofeedback system. in 25th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Proceedings,. 2003.

[13] Li, Z.H., et al., Occipital-temporal Reduction and Sustained Visual Attention Deficit in Prenatal Alcohol Exposed Adults. Brain Imaging and Behavior, 2008. 2(1): p. 39-48.

[14] Murray, S.O. and E. Wojciulik, *Attention increases neural selectivity in the human lateral occipital complex.* Nature Neuroscience, 2004. 7(1): p. 70-74.

[15] Besthorn, C., et al., *Parameters of EEG dimensional complexity in Alzheimer's disease.* Electroencephalography and Clinical Neurophysiology, 1995. 95(2): p. 84-89.

[16] Kinsner, W. A unified approach to fractal dimensions. in ICCI 2005: Fourth IEEE International Conference on Cognitive Informatics, Proceedings. 2005.

[17] Higuchi, T., *Approach to an irregular time series on the basis of the fractal theory.* Physica D: Nonlinear Phenomena, 1988. 31(2): p. 277-283.

[18] Block, A., W. Von Bloh, and H.J. Schellnhuber, *Efficient box-counting determination of generalized fractal dimensions.* Physical Review A, 1990. 42(4): p. 1869-1874.

[19] Maragos, P. and F.-K. Sun, *Measuring the fractal dimension of signals: morphological covers and iterative optimization.* IEEE Transactions on Signal Processing, 1993. 41(1): p. 108-121.

[20] Homan, R.W., J. Herman, and P. Purdy, *Cerebral location of international 10-20 system electrode placement.* Electroencephalography and Clinical Neurophysiology, 1987. 66(4): p. 376-382.

[21] *Emotiv*. Available from: http://www.emotiv.com.

[22] Laukka, S.J., et al., *Frontal midline theta related to learning in a simulated driving task.* Biological Psychology, 1995. 40(3): p. 313-320.

[23] *Simple Directmedia Layer*. Available from: http://www.libsdl.org.