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EEG SIGNAL PATTERN RECOGNITION ANALYSIS: FUZZY LOGIC SYSTEMS ASCENDANCY

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Abstract

During the last few decades, the work of neurocognitive issues within the frame of brain imaging techniques has been of considerable interest. Our approach, in this paper, concerns with the evaluation of EEG signal analysis using several pattern recognition methods. Furthermore, a comparing analysis to linear and nonlinear pattern recognition for enhanced efficiency of fuzzy logic systems has been carried out. A description of fuzzy logic principles, fuzzy logic systems and brain waves activity analysis within the frame of fuzzy logic methods is also given. Authors' future directions are to verify and enhance the theoretical and empirical findings concerning the fuzzy logic systems accuracy.

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I. Introduction

Cognitive neuroscience is the study of cognitive operations such as attention, problem-solving and memory and neurological disorders. The electroencephalogram (EEG) signal analysis studies are widely used to evaluate neurological disorders clinically [1]. Several researchers have used pattern recognition paradigms to classify EEG samples into their associated behavioral tasks [2]. However, due to the divergence in number, subject type and analysis processes, pattern recognition methods are not generally evaluated [3]. Fuzzy logic systems are considered to be an adequate tool for modeling and evaluating cognitive processes and knowledge-based systems. In this paper, linear methods like fast Fourier transform (FFT) or wavelet transform (WT) for EEG brain signal waves analysis are presented. The basic objective of this paper is pattern recognition methods related with neural and fuzzy artificial networks performance efficiency.

II. Cognitive Neuroscience

Neuroscience is the study of nervous system anatomy and physiology. It is involved with the structure and brain functions providing knowledge about how cognitive operations are carried out. A fairly recent trend in neuroscience is the integration towards cognition and it is called *cognitive neuroscience*. Cognitive neuroscience researchers use various methods to study and analyze their hypothesis. This is due to the multidisciplinary nature of this field, related to cognitive functions like attention, memory and problem-solving abilities. Within the frame of cognitive neuroscience, experimental case studies from cognitive psychology and electrophysiology functional brain imaging studies are included. Studies in patients suffering from cognitive deficits due to brain lesions constitute a vital aspect of cognitive neuroscience. Additionally, the effects of brain damage and neural circuit due to ensued damage are analyzed and evaluated.

III. EEG Brain Imaging Technique

The electroencephalogram (EEG) is the depiction of the electrical activity occurring at the surface of the brain while measuring brain waves. Brain activity is displayed on the screen of the EEG device as waveforms of diverging frequency. EEG waveforms are normally sorted according to their frequency, amplitude, shape and the respective area of the scalp which is recorded. The electroencephalogram is used for diagnosing clinically several neurological diseases. It is also used for evaluating people with brain function problems. These deficits could involve confusion, coma, tumors, long-term memory dysfunction and weakness of particular areas of the body related with a stroke, etc. [4].

The EEG recording is considered to be a safe diagnostic procedure. The electrodes record activity without causing any discomfort while the testing procedure produces no sensation. Brain waveforms reflect the cortical electrical activity which is quite small, measured in microvolts. The lowest wave frequencies of the human brain are delta waves (1Hz-4Hz) and occur during deep sleep. Theta waves are ranging from 4Hz to 8Hz and they are vivid during internal focus and meditation. Alpha waves (8Hz-13Hz) occur while a person is in an alert situation, though not during information processing. Beta wave frequencies vary from 14Hz to 20Hz and they are associated with an increased mental state activation. Gamma wave's frequency is between 25Hz to 100Hz (40Hz is considered to be the typical frequency). A decrease in gamma-band activity is probably connected with cognitive disabilities although this conjuncture is not overall confirmed.

IV. EEG Pattern Recognition Methods

There are several methods and algorithms mainly based on pattern recognition systems in order to evaluate the feature extraction and classification of EEG signals [5].

(1) Linear methods

Linear methods like fast Fourier transform (FFT) or wavelet transform (WT) are efficient in the case of stationary signals. However, assumptions of stationarity needed for the proper use of these algorithms are often ignored. WT has better accuracy comparing to FFT but a notable ambiguity in signal decomposition. With the use of linear methods, faulty results are often conducted. For instance, in the case a regular wave signal of frequency 12Hz with amplitude modulated with frequency 1Hz, the Fourier decomposition leads to two components with frequencies 11Hz and 13Hz, respectively. However, the basic frequency of the analyzed signal (12Hz) is not shown in the Fourier spectrum [12].

(a) Wavelet transform analysis

The wavelet transform is considered to be an efficient tool for EEG signals analysis related to time and frequency WT is a linear transform (time correlated with frequency) which localizes the signal information in both time and frequency as a class of functions. Therefore, the wavelet transform has been utilized widely in biomedical signal processing. In discrete wavelet analysis, a multi-resolution description is used to decompose a given signal $x(t)$ into increasingly finer detail based on two sets of basis functions, the wavelets and the scaling functions. The function for computing the signal $x(t)$ is presented in the following equation:

$$x(t) = \sum_{k} 2^{j_0/2} a_{j_0}(k) \varphi(2^{j_0} t - k) + \sum_{j=j_0}^{\infty} \sum_{k} 2^{j/2} d_j(k) \psi(2^j t - k),$$

where functions $\varphi(t)$ and $\psi(t)$ represent the basic scaling and mother wavelet, respectively. In the above expansion, the first summation represents an approximation of $x(t)$ based on the scale index of j_0, while the second term adds more detail using larger j (finer scales). The coefficients in this wavelet expansion are called the *discrete wavelet transform* (*DWT*) of the signal $x(t)$ [6].

DWT is applied for the classification and time-frequency analysis of EEG signals using wavelet coefficients. Specifically, EEG signals are decomposed into frequency sub-bands using DWT. Then a set of statistical features is extracted from these sub-bands to represent the distribution of wavelet coefficients. These statistical features are used as an input to a classifier with discrete outputs. The discrete wavelet transform (DWT) is used for recognizing and quantifying spikes, sharp waves and spike-waves and are widely used in signal processing, pattern recognition and classification [3].

(b) Fast Fourier transform

Fast Fourier transform (FFT) is a linear method applied for the EEG signals frequency analysis. FFT is a method to calculate the discrete Fourier transform while the DFT analyzes a sequence of values into components of different frequencies. The FFT function is calculated according to the following equation:

$$x(k) = \sum_{m=1}^{n} x(n) e^{-j2k\pi\frac{n}{N}},$$

where $x(n)$ is the discrete time signal, n is the discrete time, $x(k)$ is the discrete frequency representation of $x(n)$, k is the discrete frequency as a result from FFT and N is the period [7]. In order to obtain the power spectrum of the EEG signal, the output from FFT is multiplied with its own conjugate. In addition, to simplify the frequency domain analysis, the obtained FFT signal is subjected to the logarithm of base 10 [7].

(2) Vector quantization

Vector quantization (VQ) is a quantization method used for signal processing analysis. Additionally, it is used for modeling probability density functions by the distribution of prototype vectors and data compression (dividing a broad set of points into groups in order to have the same number of vectors closest to them). Each group is represented by a centroid point, as in *k*-means and several similar clustering methods. The density matching of vector quantization is essential for identifying the density of large and high-dimensioned data. Vector quantization is based on the competitive learning method similar to the self-organizing map algorithm and to auto-encoder (sparse coding models used in deep learning paradigm) [8].

(3) Artificial neural networks

Artificial neural networks (ANNs) are also used for EEG signal analysis processing. Feed-forward neural networks and multi-layer perceptron neural networks (MLPNNs) are used for approximating generic classes of functions, including continuous and integrable ones. The MLPNNs learn and generalize smaller training set requirements, fast operation and ease of implementation. Therefore, they are considered to be the most commonly used neural network architectures [3].

In most cases, the multilayer feed-forward networks are trained under a supervised method. In the case of an unsupervised classification learning, no a priori knowledge is required to define the input's membership in a particular class. This ANN is called a *self-organizing ANN* and the unsupervised classification procedure is known as clustering [9]. The most well-known self-organizing ANN is Kohonen's self-organizing feature map (SOFM) [9].

Most of pattern recognition techniques use single-feature extraction method which is followed by a predefined crisp threshold for final decision making. Nonlinear methods are commonly used, although these methods are sensitive to noise and faulty results are usually taken. Therefore, the advantages of nonlinear feature extraction methods over linear methods are essential [10].

V. Fuzzy Logic

Knowledge-based systems within the frame of fuzzy logic theory approach human cognitive processes, such as thinking and reasoning. Fuzzy logic variables may have a truth value that ranges in degree between 0 and 1. This is based on the perspective of "degrees of truth" rather than the common logic of "true or false" (else 1 or 0) of binary or Boolean logic. Fuzzy logic includes 0 and 1 as extreme cases of truth but is extended to cover the concept of partial truth. A similar process is used in fuzzy artificial neural networks and expert systems. Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. Fuzzy logic is probably closer to the way the human brain works [11].

(1) Fuzzy sets

A fuzzy set corresponds to a membership function defined in the space where the fuzzy variables are set. The membership function provides the degree of membership within the set of any element well defined according to fuzzy logic approach. The membership function maps these elements onto numerical values between the numbers zero to one. A membership function value of 0 implies that the corresponding element is definitely not an element of the fuzzy set while a value of 1 means that the element fully belongs to the set. The fuzzy set theory differs from traditional set theory because partial membership is allowed, i.e., an element can belong to a set only to a certain degree. This rate of membership is regularly referred to as the membership value and is represented using a real value in the interval $[0, 1]$, where 0 and 1 correspond to full non-membership and membership, respectively, [11].

(2) Fuzzy rules

The decision-making logic defines the way of fuzzy logic functions is performed in correlation with the knowledge base specify the outputs of fuzzy IF-THEN rules [11]. IF-THEN rules are used to create the conditional statements that consist of fuzzy logic. IF-THEN rule assumes the form where *A* and *B* are atomic terms which are evaluated by terms of fuzzy sets on the ranges *X* and *Y*, respectively. The premise of the rule '*X* is *A*' is called *antecedent* while the conclusion portion of the rule '*Y* is *B*' is called the *consequent* which makes a rule, i.e., "if *X* is *A*, then *Y* is *B*". These rules are based on natural language representation and models, based on fuzzy sets and fuzzy logic [5].

(3) Membership function (MF)

A membership function is a curve that specifies the way that each vector in the input space is mapped to a membership value or degree of membership between 0 and 1 [5]. The fuzzy logic toolbox in the case of Matlab implementation includes several built-in membership function types. Among membership function, linear function, Gaussian distribution function, sigmoid curve, straight lines, triangular, trapezoidal and quadratic-cubic polynomial curves are included [5].

(4) Fuzzy logic inference

Fuzzy inference system (FIS) is generally used for process simulation or control and is implemented either from expert knowledge or from data. The knowledge base is the one that defines the rules and the membership functions for the fuzzy rule-based system. The fuzzy inference mechanism consists of three phases. In the first phase, the values of the numerical inputs are mapped by a function according to a degree of compatibility of the respective fuzzy sets. This operation is called *fuzzification*. The process of fuzzification allows the system inputs and outputs to be expressed in linguistic terms. In the second phase, the fuzzy system processes the rules in accordance with the firing strengths of the inputs. In the third phase, the resultant fuzzy values are transformed again into numerical values. This operation is known as defuzzification. The process of defuzzification is such inverse transformation which maps the output from the fuzzy domain back into the crisp domain. Essentially, this procedure makes possible the use fuzzy logic system to deal with the decision-making procedure [11].

(5) Fuzzy score

The output is in the form of a fuzzy score, for all the inputs individual score that are about to be generated by FIS. The fuzzy score is the calculated value by FIS considering all fuzzy constraints and membership functions. The fuzzy score is decided by fuzzy rules and input variables. The fuzzy rule-based classification is evaluated for the feature extracted data set. FIS generates a score for each input signal based on the fuzzy constraints and fuzzy rules [5].

VI. Fuzzy Logic Patterns Recognition

Fuzzy logic systems can be used by means to analyze different stages of EEG classification and check the percentage of the correct recognition rate. A fuzzy neural network or neuro-fuzzy system is a learning machine which adopts parameters of a fuzzy system (i.e., fuzzy sets, fuzzy rules) using approximation techniques of neural networks. Both neural networks and fuzzy systems can be used for problem-solving, diagnostic purposes, regression or density estimation [11]. Especially fuzzy logic and fuzzy set theory are both used to describe human thinking and reasoning within a mathematical framework. They are also used for decision-making, pattern recognition, data analysis, etc. [3].

Fuzzy rule-based modeling is a qualitative modeling scheme where the system behavior is described using a natural language. A fuzzy rule-based adaptive automatic detection method consists of several steps, preprocessing, artifacts detection, feature extraction, decision-making using fuzzy logic and postprocessing. Experiment features are combined within the frame of a fuzzy rules set. The final decision was made by applying a threshold procedure to a spatial combination of multiple features. Artifacts detection algorithm was applied prior to feature extraction to identify segments corrupted with electrode movement and saturation artifacts. The information was stored to be used in postprocessing step and false detections caused by artifacts and other activities are rejected in the postprocessing steps [10].

(1) Fuzzy logic SOMF artificial neural networks

A popular self-organizing ANN is Kohonen's self-organizing feature map (SOFM). The SOFM is a single layered ANN whose weight vectors are adjusted under an unsupervised training method. SOFM has many applications, mainly in pattern recognition procedures [9]. The SOFM has been previously trained on a large training set in a self-organized learning model. Then results in an ordered set of weight vectors based on the features extracted from the training data. The trained SOFM after that functions classifier, assigning class labels to inputs based on the information held in the weight vectors of the SOFM. The spatial combination of each of the individual single channel outputs is performed by means of a fuzzy logic rule-based system [9].

(2) Fuzzy logic system as a classifier

Fuzzy logic systems can be used for data and information presentation, manipulation, recognition, interpretation and utilization. Modeling of nonlinear data with arbitrary complexity with FL is considered to be simplified in comparison to conventional statistical modeling approach. Therefore, FL can be used to classify nonlinear and non-statistical signals like EEG signals [7]. The operation of a fuzzy system is visualized in Figure 1:

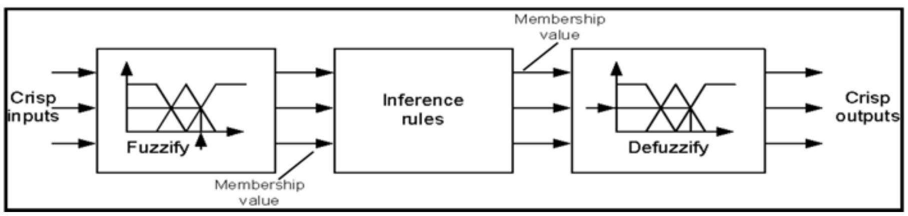

Figure 1. Operation of a fuzzy system.

The inputs are first fuzzified, inference then takes place on the fuzzy rule base and the fuzzy outcome of the rules is converted to a crisp output (defuzzification). The inputs to the fuzzy system should be essential so that fuzzy rules can be defined for the system to match the desired outputs. For each input, a membership function is, respectively, defined. The range of each membership function for every input is determined by observing the range of data for each input of data. The output of the fuzzy system is frequency range, again with corresponding membership functions (for example, low, medium and high) [7].

(3) Adaptive neuro-fuzzy inference system (ANFIS) as a classifier

A specific approach in neuro-fuzzy systems development with adaptive neuro-learning is the adaptive neuro-fuzzy inference system (ANFIS), which has shown significant results in modeling nonlinear functions. In ANFIS, the membership function parameters are extracted from a data set that defines the system behavior. The ANFIS learns features in the data set and adjusts the system parameters according to a given error criterion. ANFIS is implemented successfully for classification, modeling and data analysis [3]. The FIS structure generated from ANFIS is presented in Figure 2:

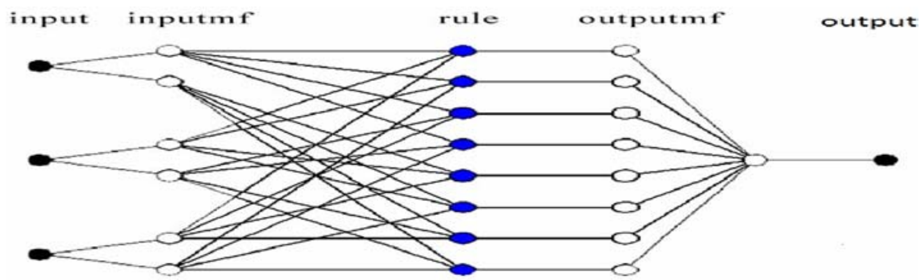

Figure 2. Adaptive neuro-fuzzy inference system (ANFIS) structure.

ANFIS combines the advantages of the neural network and fuzzy logic. An adaptive learning algorithm is applied to define the proper membership functions to adjust the input-output relationship. Additionally, fuzziness is allowed onto the inputs in order to optimize the outputs provided by nonlinear and non-statistical signals. The weights and biases of the ANN are adjusted according to training method. The accuracy of the ANN could be improved by adjusting the weights and biases of the fuzzy system and training the ANN with the use of smaller mean square error method.

Fuzzy logic toolbox of Matlab provides the functionality of ANFIS, where the neuro-adaptive learning method is applied for fuzzy modeling procedure. Additionally, it performs the training to define an improved pairing of membership function parameters [7].

VII. Discussion

In this paper, EEG pattern recognition methods have been presented, analyzed and compared. The pattern recognition and decision-making classifiers which employ fuzzy logic techniques are reviewed and evaluated.

The approach adopted enhances the idea of the consequence of the implementation of fuzzy logic methods. To allow the handling of higher levels of uncertainty in complex recognition problems, fuzzy logic systems are incorporated in methods of pattern recognition. The enhancement and verification of theoretical or experimental results obtainable making use of brain imaging methods will constitute our future work. Especially, electrophysiological brain imaging and data analysis are proposed in order to evaluate, enhance and confirm the accuracy of fuzzy logic system pattern recognition findings. Additional work and data collection procedure are on-going.

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References

[1] I. Güler and E. D. Ubeyli, Adaptive neuro-fuzzy inference system for classification of EEG signals using wavelet coefficients, J. Neurosci. Methods 148(2) (2005), 113-121.

[2] A. Gevins, G. Zeitlin, C. Yingling, J. Doyle, M. Dedon, R. Schaffer, J. Roumasset and C. Yeager, EEG patterns during 'cognitive' tasks. I. Methodology and analysis of complex behaviors, Electroencephalogr. Clin. Neurophysiol. 47(6) (1979), 693-703.

[3] A. Subasi, Application of adaptive neuro-fuzzy inference system for epileptic seizure detection using wavelet feature extraction, Comput. Biol. Med. 37(2) (2007), 227-244.

[4] A. Plerou and P. Vlamos, Evaluation of mathematical cognitive functions with the use of EEG brain imaging, Experimental Multimedia Systems for Interactivity and Strategic Innovation, I. Deliyannis, P. Kostagiolas and C. Banou, eds., IGI Global, 2016, pp. 284-306.

[5] C. Nagpal, Sleep EEG classification using fuzzy logic, Int. J. Recent Dev. Eng. Technol. 4(1) (2015), 6-12.

[6] D. Gajic, Z. Djurovic, S. Di Gennaro and F. Gustafsson, Classification of EEG signals for detection of epileptic seizures based on wavelets and statistical pattern recognition, Biomed. Eng. Appl. Basis Commun. 26(2) (2014), 1450021-1450066.

[7] R. Sudirman, A. C. Koh, N. M. Safri, W. B. Daud and N. H. Mahmood, EEG different frequency sound response identification using neural network and fuzzy techniques, 2010 6th International Colloquium on Signal Processing and its Applications, 2010, pp. 1-6.

[8] B. Amin and P. Amrutbha, Vector quantization based lossy image compression using wavelets - a review, Int. J. Innov. Res. Sci. Eng. Technol. 3(3) (2014), 10517-10523.

[9] C. J. James, R. D. Jones, P. J. Bones and G. J. Carroll, Detection of epileptiform discharges in the EEG by a hybrid system comprising mimetic, self-organized artificial neural network, and fuzzy logic stages, Clin. Neurophysiol. 110(12) (1999), 2049-2063.

[10] A. F. Rabbi and R. Fazel-Rezai, A fuzzy logic system for seizure onset detection in intracranial EEG, Comput. Intell. Neurosci. 2012 (2012), p. 705140.

[11] A. Plerou, E. Vlamou and B. Papadopoulos, Visualization of neuro-fuzzy networks training algorithms: the backpropagation algorithm approach, Experimental Multimedia Systems for Interactivity and Strategic Innovation, I. Deliyannis, P. Kostagiolas and C. Banou, eds., IGI Global, 2016, pp. 222-257.