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Vo Van Toi • Nguyen Bao Toan
Truong Quang Dang Khoa • Tran Ha Lien Phuong (Eds.)

Volume 40

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and Tran Ha Lien Phuong (Eds.)

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Vietnam

Truong Quang Dang Khoa
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Ho Chi Minh City
Vietnam

Tran Ha Lien Phuong
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Vietnam

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Preface

Welcome to the Fourth International Conference on the Development of Biomedical Engineering in Vietnam.

Vietnam is a rapidly developing, socially dynamic country, where interest in biomedical engineering activities has grown considerably in recent years. The leadership of the Vietnamese government, and of research and educational institutions, are well aware of the importance of this field for the development of the country and have instituted policies to promote its development. The political, economic and social environment within the country offers unique opportunities for the international community and this conference was intended to provide a vehicle for the sharing of experiences; development of support and collaboration networks for research; and exchange of ideas on how to improve the educational and entrepreneurial environment to better address the urgent needs of Vietnam.

In January 2004, under the sponsorship of the U.S. National Science Foundation, Professor Vo Van Toi of the Biomedical Engineering Department of Tufts University, Medford Massachusetts USA, led a U.S. delegation that consisted of Biomedical Engineering professors from different universities in the United States, and visited several universities and research institutions in Vietnam to assess the state of development of this field. This delegation proposed a five year plan that was enthusiastically embraced by the international scientific communities to actively develop collaborations with Vietnam.

Within this framework, in July 2005, the First International Conference on the Development of Biomedical Engineering in Vietnam was held in Ho Chi Minh City. From that conference a Consortium of Vietnam- International Universities was created to advise and assist the development of Biomedical Engineering in Vietnamese universities.

In July 2007, the Second International Conference on the Development of Biomedical Engineering in Vietnam was held in Hanoi. During this event the Vietnamese Association of Biomedical Science and Engineering was endorsed by the Asia-Pacific International Molecular Biology Network (AIMBN), Biomedical Engineering Society Singapore (BESS), International Federation for Medical and Biological Engineering (IFMBE), Société Française de Génie Biologique et Médical (SFGBM) and IFMBE Asia-Pacific Working Group.

In March 2009, International University (IU), established its Biomedical Engineering (BME) Department and the first accredited Engineer in BME degree in Vietnam (code: 52.42.02.04). IU is a member of Vietnam National Universities – Ho Chi Minh City (VNU-HCM), one of the two elite university networks in Vietnam, and is the first public university in Vietnam that teaches all courses in English. It was created as a new model to modernize the higher education in Vietnam. The BME Department at IU has since coordinated with its national and international counterparts to promote the activities of this field in Vietnam.

In January 2010, the Third International Conference on the Development of Biomedical Engineering in Vietnam was organized by IU in Ho Chi Minh City. It reflected the steady growth of the activities in this field in Vietnam, and featured the contributions of researchers of 21 countries, including: Australia, Belgium, Canada, Denmark, France, India, Japan, Korea, Malaysia, New Zealand, Philippines, Poland, Russia, Singapore, Spain, Switzerland, Taiwan, Thailand, United Kingdom, the United States and Vietnam. The Conference was endorsed by the International Federation for Medical and Biological Engineering (IFMBE). It also hosted the Clinical Engineering Workshop of the IFMBE Asia Pacific Working Group. The contributed papers were published in the IFMBE Proceedings Series by Springer (ISBN 978-3-642-12019-0).

This year, the Fourth International Conference on the Development of Biomedical Engineering in Vietnam is organized in Ho Chi Minh City as a ***Mega-conference***. It is kicked off by the **Regenerative Medicine Conference** (Jan 8–10, 2012) with the theme "BUILDING A FACE" USING A REGENERATIVE MEDICINE APPROACH", endorsed mainly by the Tissue Engineering and Regenerative Medicine International Society (TERMIS) and co-organized by Professor Stephen E. Feinberg, University of Michigan Health System, USA, Professor Anh Le, University of Southern California, USA and Professor Vo Van Toi, International University-VNU HCM, Vietnam. It is followed by the **Computational Medicine Conference**, endorsed mainly by the Computational Surgery International Network (COSINE) and the Computational Molecular Medicine of German National Funding Agency; and the **General Biomedical Engineering Conference**, endorsed mainly by the

International Federation for Medical and Biological Engineering (IFMBE) (Jan 10–12) and co-organized by Professor Paolo Carloni, German Research School for Simulation Sciences GmbH, Germany, Professor Marc Garbey, University of Houston, USA and Professor Vo Van Toi, International University-VNU HCM, Vietnam. It featured the contributions of 435 scientists from 30 countries, including: Australia, Austria, Belgium, Canada, China, Finland, France, Germany, Hungary, India, Iran, Italy, Japan, Jordan, Korea, Malaysia, Netherlands, Pakistan, Poland, Russian Federation, Singapore, Spain, Switzerland, Taiwan, Turkey, Ukraine, United Kingdom, United States, Uruguay and Viet Nam.

The editors would like to thank the leadership and staff of VNU-HCM and IU, local and international sponsors, and the staff and students of Biomedical Engineering Department for their valuable support for the conference and their assistance in the editing and publication of this volume.

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Erratum

Investigating Physiology of Untruth in Cerebral Cortex by Functional Near-Infrared Spectroscopy (fNIRS)

Huynh Luong Nghia[1], Truong Quang Dang Khoa[2], Tran Xuan Tan[2], Duong Duc Thien[2], Nguyen Ngoc Phuong Trinh[2], and Vo Van Toi[2]

[1] Biomedical Electronic Department, Le Quy Don Technical University, Hanoi, Vietnam
[2] Biomedical Engineering Department, International University-HCMC, Vietnam

Abtract — **Physiological measurement has been deeply investigated in microenvironment. The physiology on molecular or biochemical levels is examined to diagnose disease in early state. With new brain imaging techniques such as multi - channel near – infrared spectroscopy (NIRS), the functions of the cognitive brain activities can be determined. In this study, the relationship between specific physiology of brain cortex and psychology of untruth is assessed through measurements of the changes in concentration deoxygenated hemoglobin (HHb) and oxygenated hemoglobin (HbO2)by multi - channel NIRS. Moreover, we found the complex combination at prefrontal cortex (Cz) is related to physiology of truth and untruth.**

Keywords — **physiology of truth, physiology of untruth, prefrontal cortex, central zone, NIRS, FUSION.**

I. Introduction

With brain imaging techniques such as PET, fMRI…, the functions of cognitive brain activities can be determined**.** These techniques require strictly motion restriction, so most of participants feel stressful during experiments. However, NIRS is a non-invasive measurement.

Due to important role of untruth physiology of human being, the United States and Russia produced many devices such as Polygraph (Lie detector), детектор лжи, etc…. These techniques were used to measure and analyze data based on blood pressure, heart rate, breathe rate and electrical skin impedance…. These parameters are determined to be linked to the physiology of untruth in different levels.

In this study, multi -channel NIRS technique was used as an equipment for investigating of particular relationship between physiology of untruth and the change concentration of HbO2 and HHb in brain cortex.

II. Methodology

A. Participant

Nine healthy adults (2 female, age 19 - 22 years) have been included in our experiment. Each subject was tested three times in 180 seconds. Between tests the rest from 30 to 60 second is taken for preparing next tests. During NIRS measurements, participants had to communicate face to face with researcher and answer to his questions related to psycho-physiology of untruth.

B. Material

We acquired data of the cerebral tissue oxygenation from all participants by Shimadzu FOIRE-3000 NIRS machine (Fig. 1). This new imaging technique is designed with three different wave lengths of 780, 805 and 830 nm to monitor changes in the oxyhemoglobin (HbO), deoxyhemoglobin (DeHbO) and total hemoglobin (TotalHb).

Fig. 1 Shimadzu FOIRE-3000 NIRS machine

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III. Data analysis

There are two approach to be applied for data analyses in our study:

- Analysis based on FUSION software.
- Application by statistical mathematic.

1. Approach 1(FUSION software)

- *Method*

We used MRI-FUSION software as a tool for analyzing data in real time with NIRS measurement.

- *ROI (Region of interest)*

Right hemisphere was checked as significant cortical region where the intensive changes of HHb and HbO2 in channel 3 (Fig. 2) were observed.

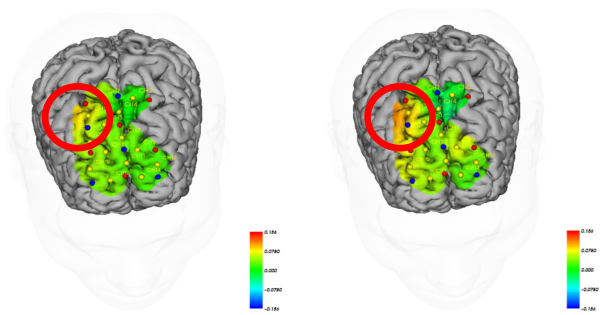

Fig. 2 The changes of HHb and HbO2 in channel 3

- *Results*

Three periods in accordance with 5th, 25th and 45th seconds of the tests are important to be under carefully examination on the changes of HHb and HbO2 concentration. Through the different colors expressing different intensiveness of HbO2 consumption at Channel 3 in three periods mentioned the untruth is checked. The period where the changes of HbO2 concentration increased higher and repeated much more than in other periods is considered as linked to untruth psycho-physiology. It was recognized that the period that much more changing in color indicated to the untruth cases. Moreover, we noticed that each participant had different level of changed colors.

2. Approach 2 (Statistical mathematic)

- *Method*

Data of each experiment was separated into three stages, in accordance with three periods (5th, 25th and 45th seconds). For each stage the statistical characteristic such as variance, mean, etc were determined. Then these characteristics were compared to that of other stages. Their maximum or minimum values (in dependence on gender) are considered as linked to untruth psycho-physiology (untruth cases).

- *Result*

Applying this method for Channel 3 given results presented in Table 1.

Table 1 The result of true test analyzed by statistical mathematic method

Date	Name	Sex	Test1	Test2	Test3
26/9	N.M.N	Male	T	T	T
	L.H.D	Male	T	1/2T	1/2T
	T.C	Female	T	2/3T	1/2T
27/9	V.N.T	Male	T	T	T
	B.N.H	Female	T	T	F
	N.M.D	Male	F	T	T
28/9	T.N.N.M	Male	T	T	F
	T.Q.V	Male	T	F	T
	D.N.H	Male		F	F
	Overall		**87%**	**70%**	**56%**

- *Notices*

- The method correctness is about 70% of tests with taking into account the participants' gender and individual differences in level adaptation and in psycho-physiology.

- The decreasing precision of method according to tests order shows the different adaptation levels of each participant in experiment

IV. Conclusion

Near – infrared spectroscopy (NIRS) is sensitive to physiology of truth. There is complex combination of cerebral cortex regions, related to physiology of untruth. The untruth states can be detected by FUSION and statistical mathematic methods. The more subtle algorithms are needed to improve results of data analysis.

V. Acknowledgement

This study was supported in partnership between Biomedical Electronic Department, Le Quy Don Technical University, Hanoi, Vietnam and Biomedical Engineering Department, International University-HCMC.We would like to thank Shimadzu Cooperation, Japan for technical support. Finally, we highly appreciate the friends who helped us in collecting information.

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High Order Moment Features for NIRS-Based Classification Problems

Tuan Hoang[1], Dat Tran[1], Khoa Truong[2], Phuoc Nguyen[1], Toi Vo Van[2], Xu Huang[1], and Dhamendra Sharma[1]

[1] Faculty of Information Sciences and Engineering, University of Canberra, Canberra, Australia
[2] Department of Biomedical Engineering, HCMC International University, Ho Chi Minh City, Viet Nam

Abstract — **This paper aims to experiment high order moment features in two well-known problems which are motor imagery and person authentication in Brain Computer Interface (BCI) systems using Near Infrared Spectroscopy (NIRS) technique. To improve performance of the systems, we propose a new feature by combining 2nd order and 4th order moments of signal together. Our results show that such the feature not only achieves very high recall and precision ratios but also is practical for online NIRS-based BCI systems. Our systems can achieve recall and precision ratio at 99.2% for the left-hand and right-hand imagery problem, and up to 100% for the person authentication problem.**

Keywords — **NIRS-based BCI, high order moment, Brain Computer Interface, motor imagery, person authentication.**

I. INTRODUCTION

Brain-Computer Interface (BCI) as defined by Wolpaw et al in [1] is "a system for controlling a device by human intentions, which does not depend on the brain's normal output pathways of peripheral nerves and muscles". A typical BCI system includes the following stages: data acquisition, data pre-processing, feature extraction, classification, device controller and feedback [2]. Many noninvasive methods have been developed to monitor brain activity. Such typical methods include Electro-encephalography (EEG), Magnetoencephalography (MEG), functional Magnetic Resonance Imaging (fMRI), Positron Emission Topography (PET), and Near-infrared spectroscopy (NIRS). This paper focuses on BCI systems based on NIRS technology.

Near-infrared spectroscopy (NIRS) is a new non-invasive optical method to acquire brain signals. This method provides researchers a range of advantages including flexibility of use, metabolic specificity, good temporal resolution, localized information, and high sensitivity in detecting small substance concentrations [3]. It also has some disadvantages such as slow operation due to the inherent latency of the hemodynamic response and weaken signal due to hair on the head. Nevertheless, NIRS's ability to record localized brain activity with a spatial resolution in the order of centimeter (depending on the probe geometry) provides us with a good mean to measure a variety of motor and cognitive activities in BCI systems [1,2].

This paper aims to experiment high order moment features in two well-known problems which are motor imagery and person authentication in Brain Computer Interface (BCI) systems using Near Infrared Spectroscopy (NIRS) technique. For NIRS-based motor imagery problem, Sitaham et al. [4] reported that they could achieve average accuracy at 73% and 89% on 2-class problem, depending on classifiers they used. Niide et al. [5] conducted similar experiments also with the 2-class problem and achieved accuracy up to 94% in general experiment and 97% in subject-specific experiment. Recently, Gottemukula et al. [6] used classification-guided feature selection in the same problem to improve the system's accuracy. For NIRS-based person authentication problem, Rowe et al [7] used discriminant analysis and Mahalanobis distance for verification task of 288 different people. The Near-infrared tissue spectra are obtained by projecting near-infrared radiation into skin on the underside of human forearms and capturing the light reflected back and out through the tissue. The instrumentation utilized was a near infrared Fourier transfer spectrophotometer manufactured by Perkin Elmer 2000. Result can attain false positive rate of 0.17% and false negative error rate of 0.0%. All of those investigations used raw or simple filtered signal as input to classifiers.

We propose a new feature by combining 2nd order and 4th order moments of NIRS signal together. RBF SVMs were used as classifiers. Our experimental results on four healthy male subjects who voluntarily participated in the experiments show that such the feature not only achieve very high recall and precision ratios but also are practical for online NIRS-based BCI systems. Our systems can achieve recall and precision ratio at 99.2% for the left-hand and right-hand imagery problem, and up to 100% for the person authentication problem.

II. MATERIALS AND METHODS

A. Subjects

Four healthy subjects who are all male and have ages range from 20 to 30 voluntarily participated in the study.

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None of the recruited subjects had neurological or psychiatric history or was on medication. Each of them gave written informed consent for the experiment. All experiments were performed at Laboratory of Biomedical Engineering Department of International University. During the experiment, subjects were sitting on a comfortable arm-chair within a dark and sound–isolated room.

B. *Experimental Procedure*

All of subjects were asked to sit on an arm-chair in front of a screen which displayed the stimuli in a dark and sound-isolated room. We used three types of protocols. The first protocol (Fig. 1a) consisted of five loops including interchange of two left-hand and two right-hand imagery loops, and a resting loop at final which totally last 130 seconds. The second (Fig. 1b) (the third protocol – Fig. 1c) consisted of four loops including three left-hand imagery loop (right-hand correspondingly) and a resting loop at final which totally last 100 seconds. A normal loop (Fig. 1d) consists of 10 seconds of resting and then 20 seconds of (left or right) imagery task. In imagery time, the subjects would clutch a ball by left hand or right hand corresponding to stimuli on screen. Each subject was asked to finish all three protocols. In total, for each subject, there were 5 trials for each type of imagery.

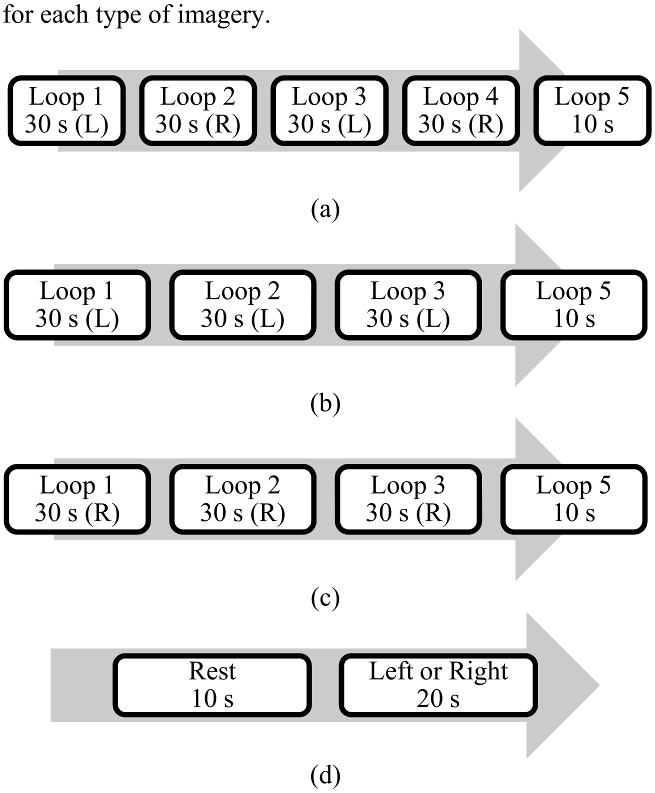

Fig. 1 (a) First protocol, (b) Second protocol, (c) Third protocol, (d) Performed tasks in a loop.

C. *Data Acquisition*

A 14-channel NIRS instrument (Shimadzu FOIRE3000) was used for acquiring oxygenated and deoxygenated hemoglobin concentration changes during our experiments. It operated at three different wavelengths of 780 nm, 805 nm and 830 nm, emitting an average power of 3 mWmm^{-2}. The detector optodes were fix placed at a distance of 3 cm from the illuminator optodes. The optodes were arranged on the left and right hemisphere of the subject's head, above the motor cortex, around C3 (left hemisphere) and C4 (right hemisphere) areas (International 10–20 System) as illustrated in Fig. 2. For each of hemisphere, we use three illuminators and three detectors. A pair of illuminator and detector optodes formed one channel. So in total, we have seven channels on each hemisphere. The photomultiplier cycles through all the illuminator–detector pairings to acquire data at every sampling period. The sampling rate is approximately 18.2 Hz. Finally, the acquired signal is digitized by the 16–bit analog to digital converter.

Fig. 2 Three illuminators and three detectors in arrangement result in 7 channels on each hemisphere where red optode illustrates illuminator and blue optode illustrates detector.

D. *Data Pre-processing*

Our fNIRS imaging system adopts near–infrared lasers of three wavelengths 780 nm, 805 nm, and 830 nm. For each channel j, optical densities $A_{j,\lambda}$ in wavelengths λ are measured. Then, from the changes in the optical density $\Delta A_{j,\lambda}$, relative concentration changes of oxy-genated hemoglobin Δoxy_j and of deoxy-genated hemoglobin $\Delta deoxy_j$ are estimated by following formula

$$\begin{pmatrix} \Delta oxy_j \\ \Delta deoxy_j \end{pmatrix} = \begin{pmatrix} -1.4887 & 0.5970 & 1.4847 \\ 1.8545 & -0.2394 & -1.0947 \end{pmatrix} \begin{pmatrix} \Delta A_{j,780} \\ \Delta A_{j,805} \\ \Delta A_{j,830} \end{pmatrix} \quad (1)$$

which is derived from the modified Beer–Lambert law and the extinction coefficients of the tissue reported by Matcher et al 2004.

Each trial was segmented into 38-data point chunks which last nearly 2 seconds. We chose 2-second chunk because it is short enough for real practical BCI systems and long enough for further processing. Two consecutive segments are overlapped by 27 data points, meaning one and a half second overlapping. Each label was labeled corresponding to class of action resting, left imagery, right imagery. We experimented responses of oxy-generated hemoglobin and deoxy-generated hemoglobin separately.

E. High Order Moment Feature Extraction

Let *y(t)* be the single channel signal we would like to extract feature. We used combination of 2nd order moment, naming mobility, and 4th order moment, naming complexity to form feature vector *v* of NIRS signal *y(t)*. In signal processing, mobility and complexity are very good at describing properties of signal.

$$Activity\big(y(t)\big) = VAR\big(y(t)\big) \tag{2}$$

$$Mobility\big(y(t)\big) = \sqrt{\frac{Activity\big(dy(t)\big)}{Activity\big(y(t)\big)}} \tag{3}$$

$$Complexity\big(y(t)\big) = \frac{Mobility(dy(t))}{Mobility(y(t))} \tag{4}$$

Because each segment has 14 channels, we extract mobility and complexity for each channel *j*. So in total, we have 28-dimension feature vectors as following $v = (Mobility_j, Complexity_j)$ with *j* ranges from channel 1 to channel 14.

F. Classification

Feature vectors then were put into classifier for training and prediction. We used only feature vector associating with left or right imagery, skipping resting segments. Two classifiers are built and trained to classify imagery tasks, left or right, and to authenticate subject. The former problem is 2-class classification and the later one is 4-class classification.

SVM has been proven as a powerful classier for solving BCI classification problems. The popular RBF kernel function $K(x, x') = e^{-\gamma\|x-x'\|^2}$ was used in our experiments. We applied grid search to get the optimal classifiers. The parameter γ was searched in $\{2^k: k = -15, -13, -11, \dots, 1, 3\}$. The trade-off parameter C was searched over the grid $\{2^k: k = -5, -3, -1, \dots, 13, 15\}$. We used 3-fold cross validation test on the training set. To eliminate effects of randomness, we used 3 repetitions in training and classification.

III. Results

A. Motor Imagery Classification Problem

Table 1 shows recall and precision for left/right motor imagery classification. It shows that our system can achieve at 99.2% for both recall and precision ratios with responses of oxy-generated hemoglobin. With responses of deoxy-generated hemoglobin, recall and precision ratios slightly increase to 99.5%.

We also tried experiments in which responses of oxy-generated and deoxy-generated hemoglobin are added together naming total hemoglobin. Results show that with total hemoglobin, our systems slightly decrease to 98.7% for both recall and precision ratios.

Table 1 Left/Right motor imagery classification results

	Oxy	Deoxy	Total
Recall	99.2	99.5	98.7
Precision	99.2	99.5	98.7

B. Person Authentication Problem

Table 2 shows recall and precision for person authentic-cation problem. It is seen that our systems could achieve very high recall and precision ratios which are nearly 100%.

Table 2 Person authentication results

	Oxy	Deoxy	Total
Recall	99.9	100	99.9
Precision	99.9	100	99.9

IV. Discussion

A. General

The above results show that the combination of mobility and complexity of NIRS signals can be a very good feature for NIRS-based BCI systems. As seen from Equation 3, mobility is calculated by taking first order differentiation of original signal. By doing so, mobility is naturally filtered without any explicitly specified filters. Similarly, as seen from Equation 4, complexity is calculated by taking second order differentiation of original signal. Hence, complexity is also naturally filtered. It is the reason we did not take any simple or complicated filters as other researchers had done. To our best knowledge, our research is the first one has used combination of mobility and complexity of signal to form feature in NIRS-based BCI systems.

Our proposed feature is not only practical in accuracy perspective but also in practical perspective. Each segment lasts approximately 2 seconds. It means that our systems need slightly more than 2 seconds (plus processing time) to make classification result based on imagery action from subjects. Moreover, by setting segment step 9 data point, resulting in one and a half second overlapping region, from the second segment, we can make decision in every half of second. This response time is very practical in almost BCI systems.

B. *Motor Imagery Classification*

As mentioned in above sections, our systems could achieve very high accuracy, up to 99.5%. Comparing with work of Gottemukula et al., our systems could produce comparable accuracy but much simpler than their system. We use no filters and no feature selection methods. Hence, our system could be more practical than their systems. Comparing with work of Niide et al. our systems could achieve better accuracy with an offset ranging from 2% to 5%. However, our experiments have less number of subjects than theirs. It could be better if we can have a standard dataset for evaluation. We also aim to conduct future experiments with more subjects and trials.

C. *Person Authentication*

For person authentication problem, our systems could achieve nearly 100% of accuracy. These results are similar with previous work of Rowe [7]. However, our experiments have much less number of participating subjects than theirs. Another important difference is that the method we used to approximate change of hemoglobin. Comparison between our results and theirs therefore is very difficult. We proved that we could apply NIRS signal in person authentication problem in small scale. In the future, we will extend the experiments size including more participants and collecting data time points.

V. Conclusion

We have proposed a new feature based on high order moment for NIRS-based BCI systems. To our best knowledge, there is no previous work proposing similar features for NIRS-bases BCI systems. By combining the 2^{nd} order and 4^{th} order moments together and using RBF SVMs as classifiers, our systems could achieve very high recall and precision ratios which are nearly 99.2% and 100% for both the left-hand and right-hand imagery problem and person authentication problem. These systems are not only high performance but also practical when running online. We believe that these features are also good at other NIRS-based problems. Our future work is to extend number of subjects participating in experiments and to collect data at some different time points.

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The address of the corresponding author:

Author: Dat Tran
Institute: Faculty of Information Science and Engineering, University of Canberra
City: ACT 2601
Country: Australia
Email: Dat.Tran@canberra.edu.au

Experiments on Synchronous Nonlinear Features for 2-Class NIRS-Based Motor Imagery Problem

Tuan Hoang[1], Dat Tran[1], Khoa Truong[2], Phuoc Nguyen[1], Toi Vo Van[2], Xu Huang[1], and Dhamendra Sharma[1]

[1] Faculty of Information Sciences and Engineering, University of Canberra, Canberra, Australia
[2] Department of Biomedical Engineering, HCMC International University, Ho Chi Minh City, Viet Nam

Abstract — **This paper aims to experiment several synchronous nonlinear features in the well-known 2-class motor imagery problem in Brain Computer Interface (BCI) systems using Near Infrared Spectroscopy (NIRS) technique. Those features including phase synchronizations and nonlinear interdependences are well known and widely applied on several neural-related problems such as epilepsy prediction. However, only a few publications are related to NIRS-based BCI systems. We conducted several experiments using NIRS technique to analyze how useful those synchronous nonlinear features can be applied on NIRS-based BCI systems. Results show that while the nonlinear interdependences can produce quite good recall and precision ratios, the phase synchronizations are not good for classification because the accuracy is as low as that in random guessing.**

Keywords — **NIRS-based BCI, nonlinear feature, synchronous feature, Brain Computer Interface, motor imagery.**

I. INTRODUCTION

Near-infrared spectroscopy (NIRS) is a new non-invasive optical method to acquire brain signals. This method provides researchers a range of advantages including flexibility of use, metabolic specificity, good temporal resolution, localized information, and high sensitivity in detecting small substance concentrations [3]. It also has some disadvantages such as slow operation due to the inherent latency of the hemodynamic response and weaken signal due to hair on the head. Nevertheless, NIRS's ability to record localized brain activity with a spatial resolution in the order of centimeter (depending on the probe geometry) provides us a good mean to measure a variety of motor and cognitive activities in Brain Computer Interface (BCI) systems [1, 2].

This paper aims to experiment several synchronous nonlinear features in the well-known 2-class motor imagery problem in BCI systems using Near Infrared Spectroscopy (NIRS) technique. Nonlinear synchronous features are widely analysed and used in several neural-related problems such as epilepsy prediction. Le et al. [8] analysed phase synchrony between neuronal signals to find large scale interactions in the brain. Their results showed that there are minor differences between the two methods and that phase synchronization measure can be used for study of neuroelectrical signals. Mirowski et al [7] conducted an important research in seizure prediction from intracranial EEG. They extracted bivariate features of several EEG synchronization measures then put them in classifiers including support vector machine (SVM), logistic regression and convolutional neural networks. Their best method outperformed previous seizure detection methods on the Freiburg dataset with 71% sensitivity and 0% false positives. Quian et al [9] experiment several synchronization measures on EEG signals. They concluded that these synchronization measures could be used in the study of synchronization in EEG data and could be of clinical relevance. For motor imagery problem based on NIRS technology, Sitaham et al. [4] reported that they could achieve average accuracy at 73% and 89% on 2-class problem, depending on classifiers they used. Niide et al. [5] conducted similar experiments also with the 2-class problem and achieved accuracy up to 94% in general experiment and 97% in subject-specific experiment. Recently, Gottemukula et al. [6] used classification-guided feature selection in the same problem to improve the accuracy.

Our research is inspired from the work of Quian et al [9]. We experiment several synchronization measures including phase synchronizations and nonlinear interdependences in NIRS-based BCI systems to see how useful those synchronization measures can provide. Results show that while the nonlinear interdependences can produce quite good recall and precision ratios, the phase synchronizations are not good for classification because the accuracy is as low as that in random guessing.

II. MATERIALS AND METHODS

A. Subjects

Four healthy subjects who are all male and have ages range from 20 to 30 voluntarily participated in the study.

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None of the recruited subjects had neurological or psychiatric history or was on medication. Each of them gave written informed consent for the experiment. All experiments were performed at Laboratory of Biomedical Engineering Department of International University in Vietnam. During the experiment, subjects were sitting on a comfortable arm-chair within a dark and sound−isolated room.

B. *Experimental Procedure*

All of the subjects were asked to sit on an arm-chair in front of a screen which displayed the stimuli in a dark and sound-isolated room. We used three types of protocols. The first protocol (Fig. 1a) consisted of five loops including interchange of two left-hand and two right-hand imagery loops, and a resting loop at final which totally last 130 seconds. The second (Fig. 1b) (the third protocol – Fig. 1c) consisted of four loops including three left-hand imagery loop (right-hand correspondingly) and a resting loop at final which totally last 100 seconds. A normal loop (Fig. 1d) consists of 10 seconds of resting and then 20 seconds of (left or right) imagery task. In imagery time, the subjects would clutch a ball by left hand or right hand corresponding to stimuli on screen. Each subject was asked to finish all three protocols. In total, for each subject, there were 5 trials for each type of imagery.

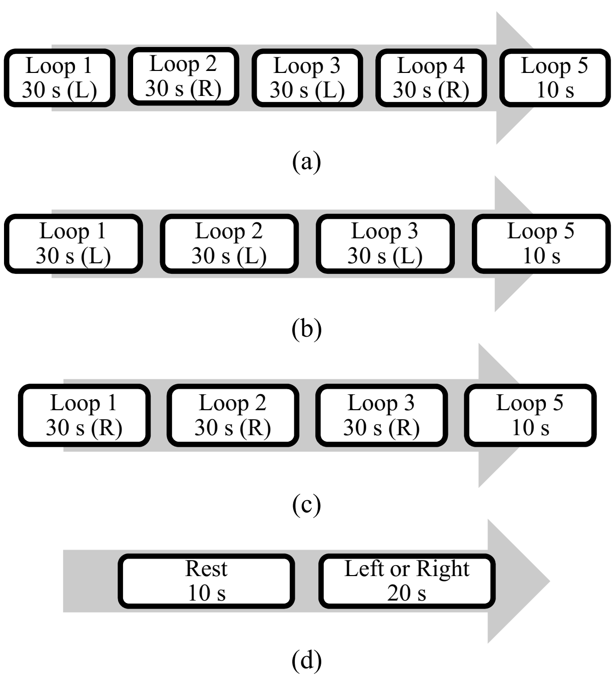

Fig. 1 (a) First protocol, (b) Second protocol, (c) Third protocol, (d) Performed tasks in a loop.

C. *Data Acquisition*

A 14-channel NIRS instrument (Shimadzu FOIRE3000) was used for acquiring oxygenated and deoxygenated hemoglobin concentration changes during our experiments. It operated at three different wavelengths of 780 nm, 805 nm and 830 nm, emitting an average power of 3 $mWmm^{-2}$. The detector optodes were fixed at a distance of 3 cm from the illuminator optodes. The optodes were arranged on the left and right hemisphere of the subject's head, above the motor cortex, around C3 (left hemisphere) and C4 (right hemisphere) areas (International 10–20 System) as illustrated in Fig. 2. For each of hemisphere, we use three illuminators and three detectors. A pair of illuminator and detector optodes formed one channel. So in total, we have seven channels on each hemisphere. The photomultiplier cycles through all the illuminator−detector pairings to acquire data at every sampling period. The sampling rate is approximately 18.2 Hz. Finally, the acquired signal is digitized by the 16−bit analog to digital converter.

Fig. 2. Three illuminators and 3 detectors in arrangement result in 7 channels on each hemisphere where red optode illustrates illuminator and blue optode illustrates detector.

D. *Data Pre-processing*

Our fNIRS imaging system adopts near−infrared lasers of three wavelengths 780 nm, 805 nm, and 830 nm. For each channel j, optical densities $A_{j,\lambda}$ in wavelengths λ are measured. Then, from the changes in the optical density $\Delta A_{j,\lambda}$, relative concentration changes of oxy-genated hemoglobin Δoxy_j and of deoxy-genated hemoglobin $\Delta deoxy_j$ are estimated by the following formula

$$\begin{pmatrix} \Delta oxy_j \\ \Delta deoxy_j \end{pmatrix} = \begin{pmatrix} -1.4887 & 0.5970 & 1.4847 \\ 1.8545 & -0.2394 & -1.0947 \end{pmatrix} \begin{pmatrix} \Delta A_{j,780} \\ \Delta A_{j,805} \\ \Delta A_{j,830} \end{pmatrix} \quad (1)$$

which is derived from the modified Beer−Lambert law and the extinction coefficients of the tissue.

Each trial was segmented into 38-data point chunks which last nearly 2 seconds. We chose 2-second chunk because it is short enough for real practical BCI systems and long enough for further processing. Two consecutive segments are overlapped by 27 data points, meaning one and a half second overlapping. Each label was labeled corresponding to class of action resting, left imagery, right imagery.

E. Nonlinear Interdependences

Let *x(t)* and *y(t)* be two discrete time series length N. State space of a signal is reconstructed and defined by embedding dimension m and time lag τ. Corresponding delay vectors are $\boldsymbol{x_n} = (x_n, x_{n-\tau}, \dots, x_{n-(m-1)\tau})$ and $\boldsymbol{y_n} = (y_n, y_{n-\tau}, \dots, y_{n-(m-1)\tau})$. Let $r_{n,j}$ and $s_{n,j}$ be the time indices of the k nearest neighbors of $\boldsymbol{x}_n$ and $\boldsymbol{y}_n$, respectively.

We define three distances naming mean squared Euclidean distance, **Y**-conditioned mean squared Euclidean distance and mean squared distance to random points as followings in order:

$$R_n^{(k)}(\boldsymbol{X}) = \frac{1}{k}\sum_{j=1}^{k}(\boldsymbol{x}_n - \boldsymbol{x}_{r_{n,j}})^2 \quad (2)$$

$$R_n^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) = \frac{1}{k}\sum_{j=1}^{k}(\boldsymbol{x}_n - \boldsymbol{x}_{s_{n,j}})^2 \quad (3)$$

$$R_n\,(\boldsymbol{X}) = \frac{1}{N-1}\sum_{j\neq n}(\boldsymbol{x}_n - \boldsymbol{x}_j)^2 \quad (4)$$

Naturally by construction in Equation (2) and (3), we always get $R_n^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) \geq R_n^{(k)}(\boldsymbol{X})$. It is easy to see that the smaller the greater difference is the stronger two signals *x(t)* and *y(t)* are correlated. It is the main idea for us to define following nonlinear interdependences.

$$S^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) = \frac{1}{N}\sum_{n=1}^{N}\frac{R_n^{(k)}(\boldsymbol{X})}{R_n^{(k)}(\boldsymbol{X}|\boldsymbol{Y})} \quad (5)$$

$$H^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) = \frac{1}{N}\sum_{n=1}^{N} ln\frac{R_n\,(\boldsymbol{X})}{R_n^{(k)}(\boldsymbol{X}|\boldsymbol{Y})} \quad (6)$$

According to Equation (3), $S^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ has values ranging from 0 to 1. The lower value of $S^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ is, the more independent the two signals are. The higher value of $S^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ is, the more synchronized two signals are. $H^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$, on the other hand, considers relations Y-condition distance with distance with random points. If $H^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) = 0$, the two signals are completely independent. If it is positive, nearness in Y could lead to nearness in X for equal time partners. Otherwise, nearness in Y could lead to farness in X.

The last nonlinear interdependence is an normalized version of $H^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$, defined as following.

$$N^{(k)}(\boldsymbol{X}|\boldsymbol{Y}) = \frac{1}{N}\sum_{n=1}^{N}\frac{R_n\,(\boldsymbol{X}) - R_n^{(k)}(\boldsymbol{X}|\boldsymbol{Y})}{R_n\,(\boldsymbol{X})} \quad (7)$$

We can see that $S^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$, $H^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ and $N^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ are not symmetric. So in general $S^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$, $H^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ and $N^{(k)}(\boldsymbol{X}|\boldsymbol{Y})$ are different from $S^{(k)}(\boldsymbol{Y}|\boldsymbol{X})$, $H^{(k)}(\boldsymbol{Y}|\boldsymbol{X})$ and $N^{(k)}(\boldsymbol{Y}|\boldsymbol{X})$, correspondingly.

F. Phase Synchronization

Analytic signals of signal *x(t)* are defined by Hilbert transform method as followings.

$$\tilde{x}(t) = (Hx)(t) = \frac{1}{\pi}P\int_{-\infty}^{\infty}\frac{x(t')}{t-t'}dt' \quad (8)$$

$$Z_x(t) = x(t) + i\tilde{x}(t) = A_x^H(t)e^{i\phi_x^H(t)} \quad (9)$$

Similarly, we can derive A_y^H and ϕ_y^H of signal *y(t)*. We then define (*a*,*b*) phase difference of *x(t)* and *y(t)*.

$$\phi_{xy}^H(t) = a\phi_x^H(t) - b\phi_y^H(t) \quad (10)$$

We say that *x(t)* and *y(t)* are a:b synchronized if their phase difference $\phi_{xy}^H(t)$ remains bounded for all *t*. If so, we define phase synchronization index as following.

$$\gamma_H = |\langle e^{i\phi_{xy}^H(t)}\rangle_t| \quad (11)$$

where brackets denote average over time. γ_H will be zero if the phases are completely not synchronized and will be 1 if they are synchronized.

G. Feature Vector

We considered four types of features: phase synchronizations, combinations of $S^k(X|Y)$ and $S^k(Y|X)$, $H^k(X|Y)$ and $H^k(Y|X)$, and $N^k(X|Y)$ and $N^k(Y|X)$. As mentioned in above section, there are 14 channels in our experiments. So in total we have 91 pairs of channel. Correspondingly, feature vectors of phase synchronizations have 91 elements while the feature vectors of the others have 182 elements.

H. Classification

Feature vectors then were put into classifier for training and prediction. We used only feature vector associating with left or right imagery, skipping resting segments. Classifiers are built and trained to classify imagery tasks, left or right motor imagery. It is a 2-class classification problem.

SVM has been proven as a powerful classifier for solving BCI classification problems. The popular RBF kernel function $K(x, x') = e^{-\gamma\|x-x'\|^2}$ was used. We applied grid search to get the optimal classifiers. The parameter γ was searched in $\{2^k : k = -15, -13, -11, \dots, 1, 3\}$. The trade-off parameter C was searched over the grid $\{2^k : k =$

$-5, -3, -1, \ldots, 13, 15\}$. We used 3-fold cross validation test on the training set. To eliminate effects of randomness, we used 3 repetitions in training and classification.

III. RESULTS

There are four parameters we need to set when running experiments: time lag, embedding dimension, Theiler correction window size, and number of nearest neighbors. In our experiments, we fixed Theiler correction window size as 5 data points, and number of nearest neighbors. For the two others, time lag varies from 1 to 3 and embedding dimension varies from 5 to 10. We also consider oxy-, deoxy- and total-hemoglobin in separate experiments. Results show that phase synchronization index is not a good feature for the 2-class NIRS-based motor imagery BCI systems. Its accuracies are about 50% which equal to random guessing for 2-class problems. In the mean while, combinations of $S^k(X|Y)$ and $S^k(Y|X)$, $H^k(X|Y)$ and $H^k(Y|X)$, and $N^k(X|Y)$ and $N^k(Y|X)$ are quite good at our systems. Table 1 shows an example of results with predefined parameters.

Table 1 Performance in accuracy (%) of systems using nonlinear interdependences as features. These experiments use following parameters: time lag=1, embedding dimension=5, Theiler correction window=5, Number of neighbors=10.

	$S^k(X\|Y)$ & $S^k(Y\|X)$	$H^k(X\|Y)$ & $H^k(Y\|X)$	$N^k(X\|Y)$ & $N^k(Y\|X)$
Oxy	78.2	74.9	75.5
Deoxy	77.6	76.6	77.1
Total	80.7	76.1	77.3

IV. DISCUSSION

One of the challenges in nonlinear feature extraction step is parameter selection. It is also true in our experiments, especially with NIRS-based systems. The disadvantage of low sampling frequency of NIRS-based systems leads to the small number of data points in single window which is 38 data point window in our systems. We cannot choose large embedding dimension and time lag because the larger embedding dimension is, the smaller size of vector in state space and the larger time lag is, the less practical information the systems are. That is also the reason our time lag varies from 1 to 3 data points, corresponding from 1/8 to 1/6 seconds, and embedding dimension varies from 5 to 10 data points, corresponding from a quarter to half of second.

Synchronization measures seem not to be a good feature for NIRS-based systems. This bad result might come from low sampling frequency of NIRS systems. Lacking of enough data points could make phase estimation and then phase synchronization index estimation turn to very bad situation. Possibly, 38 data point windows are not appropriate selection for extracting synchronization measures. However, as we discussed above, increasing window size could lead to less practical NIRS-based BCI systems.

Results also show that there are minor differences among responses of oxy-, deoxy-, and total-hemoglobin. This means that we can use any of responses without considering much about accuracy decreasing.

V. CONCLUSION

We have presented experiments using NIRS technique with different types of synchronous nonlinear features for 2-class motor imagery problem. It seems that the phase synchronization index does not work well with the problem, while the nonlinear interdependences could achieve good results with recall and precision ratios up to 80%. Future research will focus on improving performance of these systems and analyze statistical significance of the results.

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The address of the corresponding author:

Author: Dat Tran
Institute: Faculty of Information Science and Engineering, University of Canberra
City: ACT 2601
Country: Australia
Email: Dat.Tran@canberra.edu.au