

IFMBE Proceedings

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

Volume 40

4th International Conference
on Biomedical Engineering
in Vietnam



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IFMBE Proceedings Vol. 40

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

4th International Conference on Biomedical Engineering in Vietnam

Editors

Prof. Vo Van Toi
International University Vietnam
Ho Chi Minh City
Vietnam

Truong Quang Dang Khoa
International University Vietnam
Ho Chi Minh City
Vietnam

Nguyen Bao Toan
International University Vietnam
Ho Chi Minh City
Vietnam

Tran Ha Lien Phuong
International University Vietnam
Ho Chi Minh City
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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Vo Van Toi
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Truong Quang Dang Khoa
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Professor and Chair of Biomedical Engineering Department

International University - Vietnam National Universities

Quarter 6, Linh Trung, Thu Duc District

Ho Chi Minh City, Vietnam

Tel: (84-8) - 37 24 42 70 Ext. 3237

Fax: (84-8) - 37 24 42 7

Website: www.hcmiu.edu.vn/bme

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Professor, Head of Laboratory Computational Biophysics
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Professor, Center for Craniofacial Molecular Biology
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Professor and Chair of Biomedical Engineering Department
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Table of Contents

Biomedical Engineering

| | |
|--|----|
| Investigating Physiology of Untruth in Cerebral Cortex by Functional Near-Infrared Spectroscopy (fNIRS) | 1 |
| <i>Huynh Luong Nghia, Truong Quang Dang Khoa, Tran Xuan Tan, Duong Duc Thien, Nguyen Ngoc Phuong Trinh, Vo Van Toi</i> | |
| High Order Moment Features for NIRS-Based Classification Problems | 4 |
| <i>Tuan Hoang, Dat Tran, Khoa Truong, Phuoc Nguyen, Toi Vo Van, Xu Huang, Dhamendra Sharma</i> | |
| Experiments on Synchronous Nonlinear Features for 2-Class NIRS-Based Motor Imagery Problem | 8 |
| <i>Tuan Hoang, Dat Tran, Khoa Truong, Phuoc Nguyen, Toi Vo Van, Xu Huang, Dhamendra Sharma</i> | |
| Application of Transillumination Imaging to Injection Assist System | 13 |
| <i>K. Shimizu, N. Tobisawa, T.T. Nghia, T. Namita, Y. Kato</i> | |
| Design Current Stabilization Circuit for Transcranial Impulse Electro Stimulation | 17 |
| <i>Viet Dung Nguyen, Quang Huan Dao, Huu Phuong Trung Lai, Ngoc Tien Pham, Duc Thuan Nguyen, A.V. Kipensky, A.P. Lastovka</i> | |
| Feasibility Study for 3D Reconstruction of Internal Structure of Animal Body Using Near-Infrared Light | 22 |
| <i>Tran Trung Nghia, Takeshi Namita, Yuji Kato, Koichi Shimizu</i> | |
| Fabrication of Nano-piezomaterials for Powering Bioelectronics and Interfaced Cellular Biomechanics | 25 |
| <i>Thanh D. Nguyen, Michael C. McAlpine</i> | |
| The Image Reconstruction Principle in PET/CT Scanner | 30 |
| <i>Huynh Luong Nghia, Nguyen Minh Hong</i> | |
| X-Ray I _O Monitor Device for Primary Intensity Measurement in Computed Tomography (CT) Scanner | 33 |
| <i>Rafay Mehmood Siddiqui, Inam Ul Ahad, Samreen Amir, Bassim Aklan, Tahir Uddin</i> | |
| Characterization of X-Ray Sensors and Io Monitor Device Testing for Primary and Secondary Intensities Measurement | 37 |
| <i>Rafay Mehmood Siddiqui, Inam Ul Ahad, Syedah Sadaf Zehra, Anurag</i> | |
| Scheelite Coupled Photodiode X-Ray Sensor Designing and Characterization | 41 |
| <i>Inam Ul Ahad, Rafay Mehmood Siddiqui, Bassim Aklan, Syedah Sadaf Zehra</i> | |
| Bending Stiffness of IM Nails for Orthopedic Applicatins: A Comparative Study between 12 Specimen Group from 9 Established Manufacturers | 45 |
| <i>A. Ahmady, S.H. Safavai, N.A. Abu Othman</i> | |
| Retracted: A Pipelined Analog – To – Digital Converter (ADC) Using Umc 0.25 μ m Technology for Pacemaker Application | 47 |
| <i>Phan Vo Kim Anh, Hoang Trang</i> | |
| Design an Optimized CPU Architecture for Pacemaker Applications | 50 |
| <i>Le Trung Khoa, Hoang Trang</i> | |

| | |
|--|-----|
| Simple Fabrication of Exfoliated Graphene/Nafion Hybrid as Glucose Bio-sensor Electrodes | 54 |
| <i>Sun Uk Lee, Bong Gill Choi, Won Hi Hong</i> | |
| Pharmacodynamics and Pharmacokinetics of Exendin-4 Orally Delivered via an Enteric Coated Capsule Containing Nanoparticle in Diabetic Rats | 57 |
| <i>Ho-Ngoc Nguyen, Ha-Giang Nguyen</i> | |
| Roles of Nanoparticles during Magnetic Resonance Navigation and Bacterial Propulsion for Enhanced Drug Delivery in Tumors | 61 |
| <i>Sylvain Martel</i> | |
| Novel Nanoparticles for Oral Exendin-4 Delivery | 65 |
| <i>Ho-Ngoc Nguyen, Thy-Anh Bui, Ha-Giang Nguyen</i> | |
| Identifying Ovine Transcranial Acoustic Windows | 69 |
| <i>Tony de Souza-Daw, Philip M. Lewis, Robert Stewart, Paul Junor, Jerome Maller, Thang Manh Hoang, Tien Dzung Nguyen, Richard Manasseh</i> | |
| Sleep Stages Recognition Based on Combined Artificial Neural Network and Fuzzy System Using Wavelet Transform Features | 72 |
| <i>Chuang-Chien Chiu, Bui Huy Hai, Shou-Jeng Yeh</i> | |
| Lossless Image Compression Using Ideal Cross Point Regions with Wavelet Transform | 77 |
| <i>Quan Tran Nhu, Canh X. Huynh, Tin T. Dang</i> | |
| Identification and Characterization of Novel Autoantibody Biomarkers for Rheumatoid Factor-Negative and Accp-Negative Rheumatoid Arthritis | 82 |
| <i>Anh Nguyen-Hung, Binh Le-Thanh, Cindy Govart, Veerle Somers, Son Nguyen-Hong</i> | |
| Detection of Biomarker in Biopsies Based on Hr-Mas 2D HSQC Spectroscopy Indexation | 88 |
| <i>A. Belghith, C. Collet, J.P. Armspach</i> | |
| Theoretical and Experimental Investigation of a Method to Detect an Aortic Aneurysm from Pulse Waves | 92 |
| <i>H. Sato, H. Matsuhisa, H. Utsuno, K. Yamada, H. Yoshida, T. Ogura</i> | |
| Adaptive Medical Image Edge Detection in Contourlet Domain | 97 |
| <i>Nguyen Thanh Binh, Ngoc Minh Le</i> | |
| Application of Neural Network in Classifying Massive Lesions in Mammogram | 101 |
| <i>Viet Dung Nguyen, Duc Thuan Nguyen, Tien Dung Nguyen, Huu Long Nguyen, Duc Huyen Bui</i> | |
| Silicon on Insulator Microring Resonators with Feedback Waveguides for Highly Sensitive Biomedical Sensors | 105 |
| <i>Trung-Thanh Le</i> | |
| Measurement of Humidity Measurement in Adverse Conditions | 110 |
| <i>Zuoqing Guo, Yaodong Gu</i> | |
| Cell Classification Using Shape Analysis | 113 |
| <i>Thao X. Hoang, Hoan Nguyen, Son Tran, Nguyen Dinh Thuc</i> | |
| Foot Loading Character under Inner Heel Height Increasing Way | 118 |
| <i>Qi Hao, W.W. Shen, J.B. Ma, Jianshe Li, Yaodong Gu</i> | |

| | |
|---|-----|
| Table of Contents | XIX |
| Orthopedic-Based Biomechanics for Undergraduate Vietnamese Students <i>B.S. Kelley, R.M. Unruh, B.R. Rigby, H.D. Vu, Tói V. Võ</i> | 121 |
| Comparative Study of the Different Outsole Effect on Badminton Movement <i>S.D. Li, Y.D. Gu, Y.C. Lu, J.S. Li</i> | 126 |
| Development and Validation of a Gas Exclusion Technique to Allow Sterile Procedures in Non-sterile Environment <i>M.S. Salehi Dashtbayaz, B. Pingguan-Murphy, A. Ahmady, E.K. Moo</i> | 129 |
| Development of a Computer-Controlled Tactile Stimulator with Simultaneous Visual and Auditory Stimulation <i>Hyung-Sik Kim, Mi-Hyun Choi, Ji-Hye Kim, Hong-Won Yeon, Jeong-Han Yi, Soon-Cheol Chung</i> | 132 |
| Associations between Cultural Characteristics and Antibacterial Activities of Streptomyces Isolates: A Preliminary Analysis <i>Nor Asmara Tasrip, Mohd Nasir Mohd Desa, Cheah Yoke Kqueen, Chong Pei Pei, Mariana Nor Shamsudin</i> | 135 |
| Effect of Defatted Dabai (Canarium Odontophyllum Miq.) Pulp Ingestion on Lipid Peroxidation and Antioxidant Status of Hypercholesterolemic-Induced Rabbits <i>Azrina Azlan, Amin Ismail, Zulkhairi Amom, Faridah Hanim Shakirin</i> | 137 |
| Sibu Olive Inhibits Artherosclerosis by Cholesterol Lowering Effect in Cholesterol Fed-Rabbit <i>M.H. Nurulhuda, Azrina Azlan, Amin Ismail, Zulkhairi Amom, Faridah Hanim Shakirin</i> | 141 |
| Analysis of Liquid Meniscus Shape in Various Microchannels for Biomedical Diagnostic Device <i>Truong Dinh Sy, In Kyum Park, Kwang Won Hong, Hyun Chul Bang, Young Ho Seo, Byeong Hee Kim</i> | 145 |
| Microfluidic Blood Cuvette for Hemoglobin Measurement <i>J.K. Son, H.J. Kim, W.K. Jang, Y.H. Seo, B.H. Kim, W.H. Lee, K.T. Park, K.B. Nahm, E.Y. Choi</i> | 149 |
| Detection of Platelet Activation in Blood Tubing Line by Observing Ultra-Weak Luminescence <i>Ryoma Kakegawa, Toshia Fujisato</i> | 153 |
| Surface Nano-texturing of Stainless Steel for Biocompatibility Enhancement of Implantable Medical Devices <i>M. Kang, Y.M. Park, H.C. Yang, Y.H. Seo, B.H. Kim</i> | 157 |
| Blood Separation Device Based on Microstructures in Microchannels <i>Kang Il Byun, Hyun Chul Bang, Hyung Jin Kim, Eui Don Han, Young Ho Seo, Byeong Hee Kim</i> | 161 |
| Molecular Cloning of Gene Encoding for Lipoprotein in <i>Streptomyces Lividans</i> <i>Nguyen H.K. Tu</i> | 165 |
| Effects of Rice-Washing Water on the Hyaluronic Acid Production of <i>Streptococcus Thermophilus</i> <i>Nguyen H.K. Tu, Phi T.T. Trang</i> | 168 |
| Comparision of Antimicrobial Activities and Antibiotic Resistance of Lactobacillus Rhamnosus and Lactobacillus Acidophilus before and after Co-cultured <i>Nguyen H.K. Tu, Nguyen T.N. An</i> | 171 |
| Detection of N-Acetyl-D-Glucosamine in Hyaluronan by Thin Layer Chromatography <i>Nguyen H.K. Tu, Pham V.M. Thien</i> | 174 |
| A DNA Extraction Method Applied for Living Seahorses <i>Nguyen Thi Hue, Nguyen Thi Thanh Tran</i> | 178 |

| | |
|--|-----|
| Detection of Toxic <i>Aspergillus</i> Species in Food by a Multiplex PCR | 184 |
| <i>Nguyen Thi Hue, Nguyen Huu Nhlen, Pham Minh Thong, Chu Nguyen Thanh, Pham Van An</i> | |
| Evaluation of the Human Genomic DNA Extraction from Hair Root Method | 190 |
| <i>Nguyen Thi Hue, Nguyen Thi Thao Linh</i> | |
| Study of <i>Lactobacillus Acidophilus</i> by Restriction Fragment Length Polymorphism (RFLP) Analysis | 195 |
| <i>H.K. Tu Nguyen, D. Ly Ha, T.T. Vinh Doan, T. Tu Quach, H. Kim Nguyen</i> | |
| Study of Tetrodotoxin Detection in Cultured Medium | 198 |
| <i>Quach T. Tu, Doan N. Hieu, Nguyen H.K. Tu</i> | |
| Investigation of the Effects of the Histone Deacetylase Inhibitor Saha on the Medulloblastoma Cell Line Daoy Using Gel-Based Proteomics | 201 |
| <i>Thu Thuy Pham, Christian Scharf, Elke Hammer, M. Gesell, J. Sonnemann, J. Beck, Uwe Völker</i> | |
| Detection of Cholesterol Esterase in <i>Leuconostoc Dextranicum</i> Isolated in Foods | 205 |
| <i>Nguyen Hoang Khue Tu, Tran Chu Minh Hoang</i> | |
| Comparing the Effect of <i>Ficus Benjamina</i> Extract and <i>Pereskia Saecnarosa</i> Extract on the Level of Micro and Macro Minerals in Normal and Induced Liver Cancer Rats | 208 |
| <i>Asmah Rahmat, Fahmida Parveen Saib, Nurul Amira Buslima</i> | |
| Fuzzy Determination of the Human's Level of Psycho-Emotional | 213 |
| <i>Nikolay Korenevskiy, Riad Taha Al-Kasasbeh, Florin Ionescuc, Mahdi Alshamasin, E. Alkasasbeh, Andrew P. Smith</i> | |
| The Relationship between Jaw Imbalance and Arm Strength Loss through Fractal Analysis of Surface EMG Signals | 217 |
| <i>Le Minh Hoa, Truong Quang Dang Khoa, Nguyen Van Hoa, Dao Tien Tuan, Vo Van Toi</i> | |
| A Portable Respiratory Monitor Using Respiratory Inductive Plethysmography | 222 |
| <i>H.T. Ngo, C.V. Nguyen, T.M.H. Nguyen, Toi Van Vo</i> | |
| Nanoparticle-Encapsulated Tamoxifen Inducing Cytotoxic Effect on MCF-7 Breast Cancer Cell Lines | 226 |
| <i>A.M. Akim, E.E. Tung, P.P. Chong, M.Y. Hamzah, K.Z.M. Dahlan</i> | |
| Proposed Implementable Model of Computer Interfaced Electrocardiogram (ECG) Module | 229 |
| <i>Ijlal Shahrukh Ateeq, KamranHameed Muzammil Khan, Junaid Khalid, Muhammad Ali</i> | |
| Automatic Spine Extraction in Posteroanterior Radiographs Based on Spine's Features | 233 |
| <i>Phan Minh Khanh, Tran Giang Nam, Pham The Bao</i> | |
| Betulinic Acid Inhibits LPS-Induced MMP-9 Expression by Suppressing NF- κ B Activation in BV2 Microglial Cells | 238 |
| <i>Sung-Soo Kim</i> | |
| The Effects of Thrombin on Migration and Metalloproteinase Expression in C6 Glioma Cell Line, and Their Related Intracellular Signaling | 244 |
| <i>Sang-Hoon Cha</i> | |
| Diffuse Optical Tomography and Biophysical Modeling of the Aging Brain | 250 |
| <i>F. Lesage, C. Bonnerly, P. Pouliot</i> | |
| Visualization of Survival and Migration of Transplanted Stem Cells by MRI | 254 |
| <i>Tetsuji Yamaoka, Carlos A. Agudelo, Yoichi Tachibana</i> | |

| | |
|---|-----|
| Table of Contents | XXI |
| Drug Delivery System Using Polymers (Lactide–Co-Glycolide) <i>Gilson Khang</i> | 258 |
| Enhanced and Specific Internalization of Polymeric Nanoparticles to Cells <i>Kazuhiko Ishihara, Yuriko Tsukamoto, Yusuke Goto, Yuuki Inoue</i> | 262 |
| Wireless Fire Security System for Hospitals <i>Kamran Hameed, Muhammad Muzammil Khan, Ijlal Shahrukh Ateeq, Arsalan Khan, Muhammad Ali</i> | 266 |
| Wavelet Coefficient Average Value for Prediction of Motor Control Area of Human Brain Using fNIRS <i>T.N. Nguyen, T.H. Nguyen, T.T. Nguyen</i> | 270 |
| A Mean Threshold Algorithm for Human Eye Blinking Detection Using EEG <i>T. Nguyen, T.H. Nguyen, K.Q.D. Truong, Toi Van Vo</i> | 275 |
| Linear Regression Algorithm for Hand Tapping Recognition Using Functional Near Infrared Spectroscopy <i>C.Q. Ngo, T.H. Nguyen, Toi Van Vo</i> | 280 |
| Design a System of Home Health Care Telemedicine for Blood Pressure Measurement <i>N.P. Nam, N.H.M. Tam, L.G. Loc, Vo Van Toi</i> | 286 |
| Wireless Nurse Calling System <i>N.P. Nam, N.H.M. Tam, L.G. Loc, Vo Van Toi</i> | 290 |
| Survey of Personnel Who Are Operating, Repairing and Maintaining Medical Equipment in Some Hospitals in Vietnam <i>Nguyen H.M. Tam, Nguyen T.M. Linh, Pham L.T. Vy, Vo Van Toi</i> | 294 |
| Graphene Alloy with Nano Carbon: Novel Nano Material for Biosensor? <i>Nguyen Chanh Khe, Le Van Giat, Mai Ngoc Tuan Anh, Bui Thi Thu Thao, Bui Quang Thuan, Hoang Duc Truong, Bui Van Nam, Hieu Dinh</i> | 298 |
| Protein-Fatty Acid Conjugate for Self-assembled Nanoparticles in Drug Delivery <i>Beom-Jin Lee, Phuong Ha-Lien Tran</i> | 301 |
| pH-Sensitive Polymeric Systems for Controlling Drug Release in Nocturnal Asthma Treatment <i>Phuong Ha-Lien Tran, Thao Truong-Dinh Tran, Van Toi Vo, Beom-Jin Lee</i> | 304 |
| Application of l_1 Regularization for High-Quality Reconstruction of Ultrasound Tomography <i>Tan Tran-Duc, Nguyen Linh-Trung, Michael L. Oelze, Minh N. Do</i> | 309 |
| Complex Shear Modulus Estimation Using Maximum Likelihood Ensemble Filters <i>Tan Tran-Duc, Yue Wang, Nguyen Linh-Trung, Minh N. Do, Michael F. Insana</i> | 313 |
| Separation of Nonstationary EEG Epileptic Seizures Using Time-Frequency-Based Blind Signal Processing Techniques <i>Nguyen Thi Thuy-Duong, Nguyen Linh-Trung, Tan Tran-Duc, Boualem Boashash</i> | 317 |

Computational Medicine

| | |
|--|-----|
| Meta-reg: A Computational Metaheuristic Framework to Improve SVM-Based Prediction of Regulatory Activity <i>Dong Do Duc, Huan Hoang Xuan, Huy Q. Dinh</i> | 324 |
|--|-----|

| | |
|---|-----|
| Advances in Computational Identification and Modeling of DNA Regulatory Elements in the Human Genome | 328 |
| <i>Dongwon Lee, Michael A. Beer</i> | |
| Data Mining in Uniform Hospital Discharge Data Set Using Rough Set Model | 332 |
| <i>M. Park</i> | |
| Medical Image Classification and Symptoms Detection Using Fuzzy NARX Technique | 335 |
| <i>Ho Pham Huy Anh, Le Tan Loi</i> | |
| Performance Study of GPU- and FPGA-Based 3-D Monte Carlo Computation Used in Dynamic Radiation Topotherapy | 343 |
| <i>T.T. Le, J.H. Levan</i> | |
| A Useful Application of Self-recorded Photos by Mobile Phones in Maxillofacial Surgery: Case Report | 347 |
| <i>Fereydown Pourdanesh, Ashraf Sayyedi, Masoud Yaghmaei</i> | |
| Computer-Aid Cobb Measurement of Scoliosis Using Deformable Model with Fuzzy Spatial Relations | 350 |
| <i>N.B. Toan, T.Q.D. Khoa, Vo Van Toi</i> | |
| Structural Bioinformatics Approaches to Chemical Senses | 354 |
| <i>Alejandro Giorgetti</i> | |
| Uncertainty and Symmetries in DNA Sequences | 359 |
| <i>C. Cattani</i> | |
| A Numerical Model of Metastatic Colon Cancer | 370 |
| <i>Alan T. Lefor</i> | |
| Symmetry and Folded Structures of Biomolecules | 372 |
| <i>T.X. Hoang, N.T.T. Nhung, J.R. Banavar, A. Maritan</i> | |
| Diffusion, Aggregation and Penetration: Modelling the Complex Cell Envelope of E.coli | 376 |
| <i>Syma Khalid, Joseph Goose, Daniel A. Holdbrook, Thomas J. Piggot, Mark S.P. Sansom</i> | |
| Synthetic Infectious Prions | 380 |
| <i>G. Legname, N. Le Tran Thanh</i> | |
| Binding Drugs on Two Position of M2 Proton Channel and Its Mutants | 384 |
| <i>T. Hieu Nguyen, Dzong Hoang, Ly Le</i> | |
| Computational Study of Diseases Associated with Protein Aggregation | 391 |
| <i>Mai Suan Li, Ngo Son Tung</i> | |
| FIDELITY: Fuzzy Inferential Diagnostic Engine for on-Line support to physicians | 396 |
| <i>P. Sena, P. Attianese, M. Pappalardo, F. Villecco</i> | |
| Erratum | |
| A Pipelined Analog – To – Digital Converter (ADC) Using Umc 0.25 μ m Technology for Pacemaker Application | E1 |
| <i>Phan Vo Kim Anh, Hoang Trang</i> | |
| Author Index | 401 |
| Keyword Index | 405 |

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

Huynh Luong Nghia¹, Truong Quang Dang Khoa², Tran Xuan Tan², Duong Duc Thien²,
Nguyen Ngoc Phuong Trinh², and Vo Van Toi²

¹ Biomedical Electronic Department, Le Quy Don Technical University, Hanoi, Vietnam

² Biomedical Engineering Department, International University-HCMC, Vietnam

Abstract — 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

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.

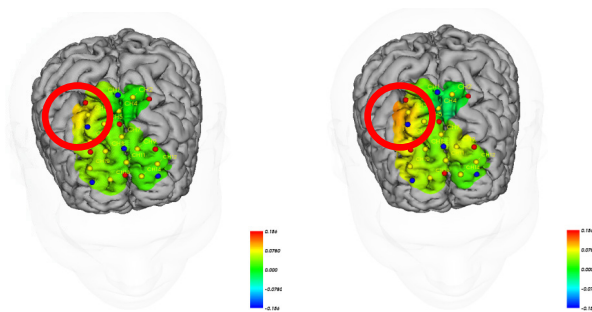


Fig. 2 The changes of HHb and HbO2 in channel 3

• 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

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High Order Moment Features for NIRS-Based Classification Problems

Tuan Hoang¹, Dat Tran¹, Khoa Truong², Phuoc Nguyen¹, Toi Vo Van², Xu Huang¹, and Dhamendra Sharma¹

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 Electroencephalography (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.

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.

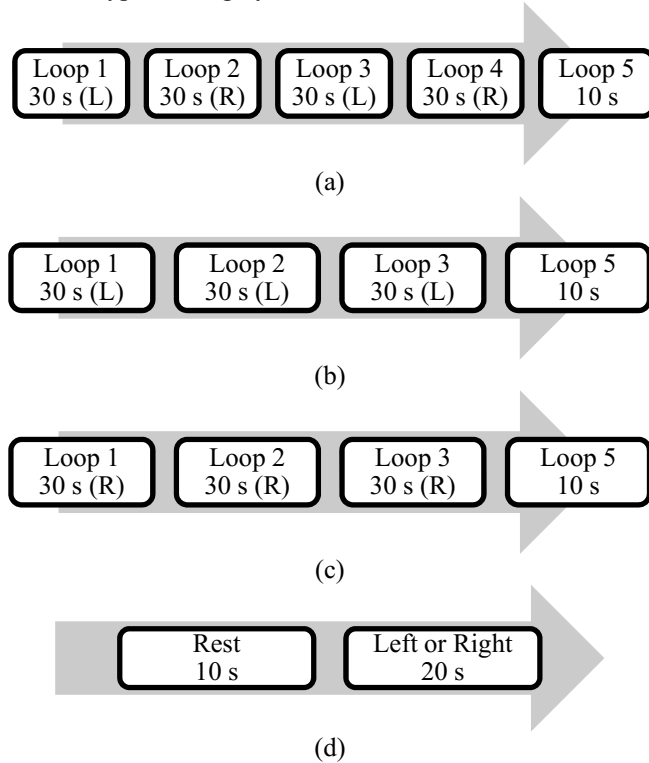


Fig. 1 (a) First protocol, (b) Second protocol, (c) Third protocol, (d) Performed tasks in a loop.

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 Δdeoxy_j are estimated by following formula

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

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.

$$Activity(y(t)) = VAR(y(t)) \quad (2)$$

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

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

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 authentication 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-based BCI systems. By combining the 2nd order and 4th 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 Hoang¹, Dat Tran¹, Khoa Truong², Phuoc Nguyen¹, Toi Vo Van², Xu Huang¹, and Dhamendra Sharma¹

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.

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.

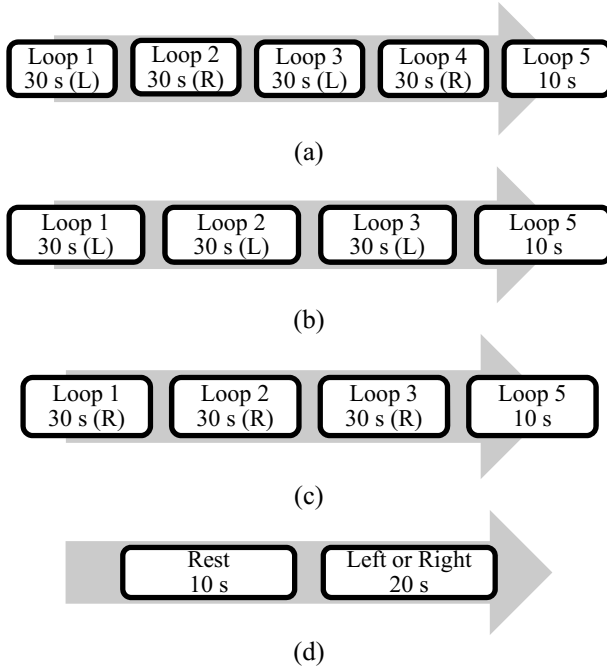


Fig. 1 (a) First protocol, (b) Second protocol, (c) Third protocol, (d) Performed tasks in a loop.

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 Δdeoxy_j are estimated by the following formula

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

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 $\mathbf{x}_n = (x_n, x_{n-\tau}, \dots, x_{n-(m-1)\tau})$ and $\mathbf{y}_n = (y_n, y_{n-\tau}, \dots, y_{n-(m-1)\tau})$. Let $r_{n,j}$ and $s_{n,j}$ be the time indices of the k nearest neighbors of \mathbf{x}_n and \mathbf{y}_n , respectively.

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

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

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

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

Naturally by construction in Equation (2) and (3), we always get $R_n^{(k)}(\mathbf{X}|\mathbf{Y}) \geq R_n^{(k)}(\mathbf{X})$. 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.

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

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

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

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

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

We can see that $S^{(k)}(\mathbf{X}|\mathbf{Y})$, $H^{(k)}(\mathbf{X}|\mathbf{Y})$ and $N^{(k)}(\mathbf{X}|\mathbf{Y})$ are not symmetric. So in general $S^{(k)}(\mathbf{X}|\mathbf{Y})$, $H^{(k)}(\mathbf{X}|\mathbf{Y})$ and $N^{(k)}(\mathbf{X}|\mathbf{Y})$ are different from $S^{(k)}(\mathbf{Y}|\mathbf{X})$, $H^{(k)}(\mathbf{Y}|\mathbf{X})$ and $N^{(k)}(\mathbf{Y}|\mathbf{X})$, 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 $S^k(\mathbf{X}|\mathbf{Y})$ and $S^k(\mathbf{Y}|\mathbf{X})$, $H^k(\mathbf{X}|\mathbf{Y})$ and $H^k(\mathbf{Y}|\mathbf{X})$, and $N^k(\mathbf{X}|\mathbf{Y})$ and $N^k(\mathbf{Y}|\mathbf{X})$. 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 $K(\mathbf{x}, \mathbf{x}') = e^{-\gamma \|\mathbf{x} - \mathbf{x}'\|^2}$ 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 $\{2^k: k =$

$-5, -3, -1, \dots, 13, 15\}$. 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

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