

SPRINGER BRIEFS IN
ELECTRICAL AND COMPUTER ENGINEERING

Christoph Guger

Brendan Allison

Mikhail Lebedev *Editors*

Brain-Computer Interface Research

A State-of-the-Art
Summary 6



Springer

SpringerBriefs in Electrical and Computer Engineering

Series editors

Woon-Seng Gan, Nanyang Technological University, Singapore, Singapore

C.-C. Jay Kuo, University of Southern California, Los Angeles, CA, USA

Thomas Fang Zheng, Tsinghua University, Beijing, China

Mauro Barni, University of Siena, Siena, Italy

More information about this series at <http://www.springer.com/series/10059>

Christoph Guger · Brendan Allison
Mikhail Lebedev
Editors

Brain-Computer Interface Research

A State-of-the-Art Summary 6

 Springer

Editors

Christoph Guger
g.tec Guger Technologies OG
Schiedlberg
Austria

Mikhail Lebedev
Department of Neurobiology
Duke University
Durham, NC
USA

Brendan Allison
g.tec Guger Technologies OG
Schiedlberg
Austria

ISSN 2191-8112 ISSN 2191-8120 (electronic)
SpringerBriefs in Electrical and Computer Engineering
ISBN 978-3-319-64372-4 ISBN 978-3-319-64373-1 (eBook)
DOI 10.1007/978-3-319-64373-1

Library of Congress Control Number: 2017938537

© The Author(s) 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Contents

Introduction	1
Christoph Guger, Brendan Z. Allison and Mikhail A. Lebedev	
Advances in BCI: A Neural Bypass Technology to Reconnect the Brain to the Body	9
Gaurav Sharma, Nicholas Annetta, David A. Friedenberg and Marcia Bockbrader	
Precise and Reliable Activation of Cortex with Micro-coils	21
Seung Woo Lee and Shelley I. Fried	
Re(con)volution: Accurate Response Prediction for Broad-Band Evoked Potentials-Based Brain Computer Interfaces	35
J. Thielen, P. Marsman, J. Farquhar and P. Desain	
Intracortical Microstimulation as a Feedback Source for Brain-Computer Interface Users	43
Sharlene Flesher, John Downey, Jennifer Collinger, Stephen Foldes, Jeffrey Weiss, Elizabeth Tyler-Kabara, Sliman Bensmaia, Andrew Schwartz, Michael Boninger and Robert Gaunt	
A Minimally Invasive Endovascular Stent-Electrode Array for Chronic Recordings of Cortical Neural Activity	55
Thomas J. Oxley, Nicholas L. Opie, Sam E. John, Gil S. Rind, Stephen M. Ronayne, Anthony N. Burkitt, David B. Grayden, Clive N. May and Terence J. O'Brien	
Visual Cue-Guided Rat Cyborg	65
Yueming Wang, Minlong Lu, Zhaohui Wu, Xiaoxiang Zheng and Gang Pan	

Predicting Motor Intentions with Closed-Loop Brain-Computer Interfaces	79
Matthias Schultze-Kraft, Mario Neumann, Martin Lundfall, Patrick Wagner, Daniel Birman, John-Dylan Haynes and Benjamin Blankertz	
Towards Online Functional Brain Mapping and Monitoring During Awake Craniotomy Surgery Using ECoG-Based Brain-Surgeon Interface (BSI)	91
L. Yao, T. Xie, Z. Wu, X. Sheng, D. Zhang, N. Jiang, C. Lin, F. Negro, L. Chen, N. Mrachacz-Kersting, X. Zhu and D. Farina	
A Sixteen-Command and 40 Hz Carrier Frequency Code-Modulated Visual Evoked Potential BCI	97
Daiki Aminaka and Tomasz M. Rutkowski	
Trends in BCI Research I: Brain-Computer Interfaces for Assessment of Patients with Locked-in Syndrome or Disorders of Consciousness	105
Christoph Guger, Damien Coyle, Donatella Mattia, Marzia De Lucia, Leigh Hochberg, Brian L. Edlow, Betts Peters, Brandon Eddy, Chang S. Nam, Quentin Noirhomme, Brendan Z. Allison and Jitka Annen	
Recent Advances in Brain-Computer Interface Research—A Summary of the BCI Award 2016 and BCI Research Trends	127
Christoph Guger, Brendan Z. Allison and Mikhail A. Lebedev	

Introduction

Christoph Guger, Brendan Z. Allison and Mikhail A. Lebedev

1 What Is a BCI?

Brain-computer interfaces (BCIs) are devices that directly read brain activity and use it in a real-time, closed loop system with feedback to the user. Unlike all other interfaces, BCIs do not require movement. Instead, the information from the brain is translated into messages or commands without relying on the body's natural output pathways. Thus, BCIs can be very helpful to people with severe motor disabilities that prevent them from speaking or using most (or even all) other devices for communication.

BCI research has continued to provide new ways to help these types of patients. In the last several years, BCIs have also broadened far beyond communication and control devices for severely paralyzed users. Today, BCIs are rapidly gaining attention for people with a wide variety of other conditions. Major entities and individuals such as Facebook and Elon Musk have recently announced extremely ambitious BCI-related projects. These research activities and announcements could lead to new ways to help many more people, and new hope for future developments. On the other hand, announcements of overly ambitious and unrealistic goals could lead to false hope and sour public opinion. It is certainly a dynamic and eventful time for the BCI research community.

C. Guger (✉)
Schiedlberg, Austria
e-mail: guger@gtec.at

B.Z. Allison
San Diego, USA

M.A. Lebedev
Durham, USA

© The Author(s) 2017
C. Guger et al. (eds.), *Brain-Computer Interface Research*, SpringerBriefs
in Electrical and Computer Engineering, DOI 10.1007/978-3-319-64373-1_1

1

2 The Annual BCI-Research Award

G.TEC is a leading provider of hardware, software, and complete systems for BCI research and related directions. G.TEC is headquartered in Austria and with branches in Spain and the USA. In 2010, G.TEC decided to create an Annual BCI-Research Award to recognize and study top new BCI projects. The competition is open to any BCI group worldwide. There is no limitation or special consideration for the type of hardware and software used in the submission. Since the first award in 2010, we have followed more or less the same process:

- G.TEC selects a Chairperson of the Jury from a well-known BCI research institute.
- This Chairperson forms a jury of top BCI researchers who can judge the Award submissions.
- G.TEC publishes information about the BCI Award for that year, including submission instructions, scoring criteria, and a deadline.
- The jury reviews the submissions and scores each one across several criteria. The jury then determines twelve nominees and one winner.
- The nominees are announced online, asked to contribute a chapter to this annual book series, and invited to a Gala Award Ceremony that is attached to a major conference (such as an International BCI Meeting or Conference).
- At this Gala Award Ceremony, the twelve nominees each receive a certificate, and the winner is announced. The winner earns \$3000 USD and the prestigious trophy. The 2nd place winner gets \$2000 USD and the 3rd place gets \$1000 USD.

We have made some changes over the years, such as increasing the number of nominees from ten to twelve and adding second and third place awards. Otherwise, the overall process has not changed. The 2016 jury was:

Mikhail A. Lebedev (chair of the jury 2016),
Alexander Kaplan,
Klaus-Robert Müller,
Ayse Gündüz,
Kyoussuke Kamada,
Guy Hotson.

Consistent with tradition, the jury included the winner from the preceding year (Guy Hotson). The chair of the jury, Dr. Mikhail A. Lebedev, is a top figure in BCI research and leads the prestigious BCI lab at Duke University, USA. Dr. Mikhail Lebedev said: “I was very fortunate to work with the 2016 jury. All of the jury members that I approached chose to join the jury, and we had an outstanding team”.

How does the jury decide the nominees and winners? We have used the same scoring criteria across different years. These are the criteria that each jury uses to score the submissions. Earning a nomination (let alone an award) is very

challenging, given the number of submissions and the very high quality of many of them. Submissions need to score well on several of these criteria:

- Does the project include a novel application of the BCI?
- Is there any new methodological approach used compared to earlier projects?
- Is there any new benefit for potential users of a BCI?
- Is there any improvement in terms of speed of the system (e.g. bit/min)?
- Is there any improvement in terms of accuracy of the system?
- Does the project include any results obtained from real patients or other potential users?
- Is the used approach working online/in real-time?
- Is there any improvement in terms of usability?
- Does the project include any novel hardware or software developments?

3 The BCI Book Series

The annual BCI Book Series is another way that we recognize and study the top BCI projects over time. Each year, the nominees are invited to contribute a chapter. The authors have considerable flexibility in their chapters. Aside from their nominated work, authors might present even newer achievements, work from related groups, or future directions and challenges. In addition to the work that was nominated, authors may also present related material, such as new work since their submission. We have also had some flexibility across different years, such as including chapters from “honorable mention” submissions that were not nominated but had new improvements since their submission (Figs. 1 and 2).

In addition to providing the authors with flexibility, we also asked them to present material in a relatively readable format. While chapters present advanced work, the authors and editors have worked to explain some underlying concepts and why the work is important. The chapters include numerous color figures to help illustrate the authors’ ideas and results. Thus, we hope that the chapters herein are of interest not only to experts in different fields, but also to non-experts. For example, chapters might be useful for students who are enrolled in a relevant course or are considering a new research or career direction.

Each book also contains an introduction and conclusion. Across different years, we have used the submissions, nominees, and winners to study trends and issues within BCI research. These chapters have already led to some conclusions about what has and hasn’t changed. For example, the types of imaging approaches that are described in submitted and nominated projects has been fairly consistent over the years. EEG-based approaches are prevalent, while intracranial methods including ECoG and depth electrodes are fairly well represented, and other approaches such as fMRI and fNIRS are relatively less common. Most submissions, nominees, and winners have come from the USA and Europe, with some submissions from Japan and China, and many projects that span different groups.



Fig. 1 This picture shows the nominees at the BCI Award 2016 ceremony. Tomek Rutkowski, Eberhard Fetz, Jaime Pereira, Benjamin Blankertz, Jordy Thielen, Shelley I. Fried, Lin Yao, Sharlene Flesher, Gaurav Sharma, Kyoussuke Kamada (jury), and Christoph Guger (organizer)



Fig. 2 Christoph Guger (organizer), Sharlene Flesher (nomination), and Kyoussuke Kamada (jury)

What has changed? The types of applications and patient groups have broadened considerably over the years. In 2010, projects were relatively focused on communication and control for persons with severe motor disabilities. Recently, many more projects have presented achievements such as assessment of consciousness, rehabilitation, and functional brain mapping, which could benefit persons with disorders of consciousness (DOC), stroke, brain injury, cerebral palsy, epilepsy, tumors, and other conditions. These and other developments that we have noted in prior books are consistent with, and often precede, more general consensus across other BCI publications. This year might introduce other new directions that will soon become prominent. For example, projects focusing on sensory restoration and new directions with intracranial BCIs were nominated, which are directions that were also nominated in recent years. Two of the 2016 nominees explored autism, and another 2016 nominee included a new game that also addresses classic issues in free will.

This year, we have decided to extend our focus on growing trends and issues with a new type of chapter: “Trends in BCI Research”. This is a new type of chapter that spans different authors and research groups, including some nominees and winners along with top outside experts. Each year, our book may include one or more of these special chapters that highlights a topical research field. Our first such chapter focuses on BCI technology for persons with disorders of consciousness (DOCs). This direction has advanced well beyond initial research. Several groups worldwide have published dozens of papers that include bedside assessment, communication, and/or outcome prediction with patients in real-world settings. Our new chapter includes recent achievements from different groups that were presented at the BCI Meeting 2016 in Pacific Grove, CA, the same conference where the 2016 BCI Awards Ceremony occurred.

4 Projects Nominated for the BCI Award 2016

This year’s jury reviewed all of the submissions based on the scoring criteria presented above. After tallying the scores across all reviewers, the twelve submissions that were nominated for a BCI Award 2016 were:

A P300-based brain-computer interface for social attention rehabilitation in autism

Carlos Amaral¹, João Andrade¹, Marco Simões¹, Susana Mouga^{1,2}, Bruno Direito¹, Miguel Castelo-Branco^{1,3}

- 1 IBILI-Institute for Biomedical Imaging and Life Sciences, Faculty of Medicine—University of Coimbra, Coimbra, Portugal
- 2 Unidade de Neurodesenvolvimento e Autismo do Serviço do Centro de Desenvolvimento da Criança, Pediatric Hospital, Centro Hospitalar e Universitário de Coimbra, Coimbra, Portugal
- 3 ICNAS—Brain Imaging Network of Portugal.

Sixteen Commands and 40 Hz Carrier Frequency Code-modulated Visual Evoked Potential BCI

Daiki Aminaka, Tomasz M. Rutkowski
University of Tsukuba, Japan.

Natural movement with concurrent brain-computer interface control induces persistent dissociation of neural activity

Luke Bashford^{1,2}, Jing Wu³, Devapratim Sarma³, Kelly Collins⁴, Jeff Ojemann⁴, Carsten Mehring²

- 1 Imperial College London, Bioengineering, UK
- 2 Bernstein Centre, Faculty of Biology, BrainLinks-BrainTools, Univ. of Freiburg, Germany
- 3 Bioengineering, Ctr. For Sensorimotor Neural Eng.
- 4 Dept. of Neurolog. Surgery, Ctr. For Sensorimotor Neural Eng., Univ. of Washington, USA.

Intracortical Microstimulation as a Feedback Source for Brain-Computer Interface Users

Sharlene Flesher^{2,3}, John Downey^{2,3}, Jennifer Collinger^{1,2,3,4}, Stephen Foldes^{1,3,4}, Jeffrey Weiss^{1,2}, Elizabeth Tyler-Kabara^{1,2,5}, Sliman Bensmaia⁶, Andrew Schwartz^{2,3,8}, Michael Boninger^{1,2,4}, Robert Gaunt^{1,2,3}

- 1 1,2,5,8 Departments of Physical Medicine and Rehabilitation, Bioengineering, Neurological Surgery, Neurobiology, University of Pittsburgh, Pittsburgh, PA, USA
- 2 3 Center for the Neural Basis of Cognition, Pittsburgh, PA, USA
- 3 4 Department of Veterans Affairs Medical Center, Pittsburgh, PA, USA
- 4 6 Department of Organismal Biology and Anatomy, University of Chicago, Chicago, IL, USA.

Minimally invasive endovascular stent-electrode array for high-fidelity, chronic recordings of cortical neural activity

Thomas J. Oxley, Nicholas L. Opie, Sam E. John, Gil S. Rind, Stephen M. Ronayne, Clive N. May, Terence J. O'Brien
Vascular Bionics Laboratory, Melbourne Brain Centre, Departments of Medicine and Neurology, The Royal Melbourne Hospital, The University of Melbourne, Parkville, Victoria, Australia.

Brain-Computer Interfaces based on fMRI for Volitional Control of Amygdala and Fusiform Face Area: Applications in Autism

Jaime A. Pereira^{1,2}, Ranganatha Sitaram^{1,3}, Pradyumna Sepulveda^{2,4,5}, Mohit Rana², Cristián Montalba⁵, Cristián Tejos^{3,4,5}, Sergio Ruiz^{1,2,3}

- 1 Department of Psychiatry and Interdisciplinary Center for Neuroscience, School of Medicine, Pontificia Universidad Católica de Chile
- 2 Laboratory of Brain-Machine Interfaces and Neuromodulation, Pontificia Universidad Católica de Chile

- 3 Institute for Medical and Biological Engineering, Schools of Engineering, Medicine and Biology, Pontificia Universidad Católica de Chile
- 4 Department of Electrical Engineering, Pontificia Universidad Católica de Chile.
- 5 Biomedical Imaging Center, Pontificia Universidad Católica de Chile.

Reclaiming the Free Will: A Real-Time Duel between a Human and a Brain-Computer Interface

Matthias Schultze-Kraft, Daniel Birman, Marco Rusconi, Carsten Allefeld, Kai Görgen, Sven Dähne, Benjamin Blankertz, John-Dylan Haynes
Neurotechnology Group, Technische Universität Berlin, Berlin, Germany.

An Implanted BCI for Real-Time Cortical Control of Functional Wrist and Finger Movements in a Human with Quadriplegia

Gaurav Sharma¹, Nick Annetta¹, Dave Friedenberg¹, Marcie Bockbrader², Ammar Shaikhouni², W. Mysiw², Chad Bouton¹, Ali Rezaei²

- 1 Battelle Memorial Institute, 505 King Ave, Columbus, OH 43201
- 2 The Ohio State University, Columbus, OH, USA 43210.

Broad-band BCI: finding structure in noisy data

Jordy Thielen, Pieter Marsman, Colleen Monaghan, Jason Farquhar and Peter Desain
Donders Center for Cognition, Radboud University Nijmegen

Vision-Augmented Rat Cyborg

Yueming Wang¹, Minlong Lu², Zhaohui Wu², Liwen Tian², Kedi Xu¹, Xiaoxiang Zheng¹, Gang Pan²

- 1 Qiushi Academy for Advanced Studies, Zhejiang University, China.
- 2 College of Computer Science, Zhejiang University, China

Precise and reliable activation of cortex with micro-coils

Seung Woo Lee and Shelley I. Fried
Boston VA Healthcare System, Boston, Massachusetts, USA, Department of Neurosurgery, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA.

Towards Online Functional Brain Mapping and Monitoring during Awake Craniotomy Surgery using ECoG-based Brain-Surgeon Interface (BSI)

L. Yao¹, T. Xie², Z. Wu³, X. Sheng², D. Zhang², C. Lin¹, F. Negro¹, L. Chen³, N. Mrachacz-Kersting⁴, X. Zhu², D. Farina¹

- 1 Institute of Neurorehabilitation Systems, University Medical Center Goettingen, Goettingen, Germany.
- 2 State Key Laboratory of Mechanical System and Vibration, Institute of Robotics, Shanghai Jiao Tong University, Shanghai, China.
- 3 Department of Neurosurgery, Huashan Hospital, Fudan University, China.⁴⁴
Center for Sensory-Motor Interaction, Aalborg University, Aalborg, Denmark.

5 Summary

Since 2010, the annual BCI Awards and book series have recognized the top BCI projects worldwide. Our books have also identified and highlighted major trends and issues in BCI research. The procedures relating to jury selection, scoring criteria, and the awards have been updated somewhat over the years, and this book introduces the new Trends in BCI Research chapter. We plan to continue administering and editing the BCI Awards and book series, and look forward to next year's submissions!

3 Conclusion and Future Directions

The Annual BCI-Research Awards, along with this book series, have sought to recognize and identify the newest and best developments in BCI research. As these efforts continue over the years, we have more and more data we can use to explore

different trends, and we may consider a specialized chapter or other article that just focused on trends and a retrospective. In the short term, however, we are focused on the next award. The 2017 BCI-Award flyer was posted online (see Fig. 3), and the deadline of June 15, 2017 has expired. The jury is currently scoring the submissions, and the awards ceremony will occur with the Seventh International BCI Conference in Graz, Austria in September 2017.

We are proud to announce the jury for 2017:

Natalie Mrachacz-Kersting (chair of the jury 2017),
Gaurav Sharma (winner 2016),
Reinhold Scherer,
Jose Pons,
Femke Nijboer,
Kenji Kansaku,
Aaron Batista,
Jing Jin.

This is a particularly large jury, and contains even more breadth than usual. The jury includes specialists in different imaging, signal processing, and output methods, rehabilitation, ethics, robotics, virtual reality, and numerous other BCI-related fields. The 2017 jury also has very good representation from BCI groups around the world. The chair comes from a top Danish BCI institute. Mrachacz-Kersting is a professor in the Neural Engineering and Neurophysiology lab of Aalborg University. The jury also includes experts who work in different European countries, the USA, China, and Japan.

In summary, the 2016 BCI Awards and the resulting chapters have introduced and recognized many of the most innovative and promising new projects in the BCI research community. Most of the nominees come from well-known, established groups that are currently exploring even newer directions based on their nominated projects. We have also explored different trends in BCI research by analysing different characteristics of the submissions. We hope and expect that the 2017 BCI Awards will highlight another group of new and fascinating ideas, and further recognize new and developing trends.