

University of Bremen  
Institute of Automation  
Otto-Hahn-Allee NW1  
D-28359 Bremen

# **BRAINROBOT**

## **Methods and Applications for Brain Computer Interfaces**

Axel Gräser  
Ivan Volosyak (Eds.)

Shaker Verlag  
Aachen 2010



Publication Series of the Institute of Automation  
University of Bremen

Series 5-Nr.2

**Axel Gräser,  
Ivan Volosyak (Eds.)**

## **BRAINROBOT**

Methods and Applications for Brain Computer Interfaces

Shaker Verlag  
Aachen 2010

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

**Publication Series of the INSTITUTE OF AUTOMATION, UNIVERSITY OF BREMEN:**

- 1 Colloquium of Automation, Salzhausen
- 2 Automation
- 3 Robotics
- 4 Control Theory
- 5 Brain Computer Interface
- 6 Virtual and Augmented Reality
- 7 Image Processing

Copyright Shaker Verlag 2010

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8322-8201-1

ISSN 1861-5457

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: [www.shaker.de](http://www.shaker.de) • e-mail: [info@shaker.de](mailto:info@shaker.de)

# Preface

This booklet contains the results of the EU-Marie-Curie-Transfer of Knowledge (TOK) project BRAINROBOT MTKD-CT-2004-014211. The different chapters contain mainly enlarged versions of already published papers. The collection should give the reader a complete overview about the project and the different approaches which have been taken into account. The overall goal of BRAINROBOT was the transfer of knowledge by research in the fast growing field of Brain Computer Interfaces (BCI). The TOK aimed to provide a fast BCI to be used as an input device for high-level control of the care-giving robot FRIEND. The necessary interdisciplinary research required a close cooperation between experts from different areas such as Cognitive Neurosciences and Robotics. The research project was funded by the EU Marie Curie Transfer of Knowledge (TOK) funding scheme, which is unique in the form of financing it, provides funds for the transfer of knowledge between institutions with quite different backgrounds and experiences. The host institute and project coordinator of the BRAINROBOT project, the Institute of Automation (IAT) at the University of Bremen in Germany, has many years of experience in robotics, especially in the field of care-providing robots. The partners in the project consortium were Professor Dr. Pfurtscheller and Professor Dr. Neuper, Institute for Knowledge Discovery, Graz University of Technology, Graz, Austria; Professor Dr. Niels Birbaumer, University of Tübingen, Tübingen, Germany; Dr. Alexa Riehle, Institute de Neurosciences Cognitives de la Méditerranée, CNRS Marseille, France; Prof. Dr. Ken Hunt and Dr. Henrik Gollee, Department of Mechanical Engineering, Centre for Systems and Control, University of Glasgow, Glasgow, UK. The experience of the partners was, among others, in Cognitive Neuroscience, Brain-Computer Interface and Functional Electrical Stimulation (FES). Incoming and outgoing experienced and incoming senior researchers were also involved in the project. In total 108 person months were financed by the project. The person months financed were distributed as follows: 81 person months for incoming experienced scientists, 21 person months for outgoing scientists from the IAT who spent time at the partner institutes and 6 person months for senior researchers. The TOK was carried out in several research projects which led to a considerable number of publications. IAT realized control of the care-giving robot FRIEND with a BCI-system and demonstrated that even BCI-inexperienced users were able to control the robot by brain signals. The BCI-robot control was successfully presented at the International Conference on Rehabilitation Robotics ICORR in 2007 and the international fairs CEBIT and RehaCare in 2008. The participation in CEBIT 2008 and RehaCare 2008 enabled a field test of IAT's BCI with users of different ages, including disabled users.

Even in the early stages of the BRAINROBOT research project, it became obvious that the delay time of BCIs and the low information transfer rate are very big obstacles for the use of BCI for robot control. Several successor research projects resulted from this experience (BRAIN, sBCI) which have as goals, among others, increasing

the information transfer rate and shortening the response time of BCIs. Due to the structure and funding opportunities of the EU Marie Curie Transfer of Knowledge scheme, the IAT was able to build strong knowledge base in BCI systems in a very short time. The IAT experienced researchers had the opportunity to visit several first class institutes where they gained knowledge about BCI and FES. The Marie Curie Transfer of Knowledge funding also enabled IAT to hire first class experienced researchers to carry out research at the IAT while transferring their knowledge to the IAT researchers and doctoral students. IAT was also able to invite, for short periods, senior researchers who are first class experts in their field of research to share and transfer their specific knowledge.

I would like to thank the EU for the creation of the TOK funding scheme. I would like especially to thank my colleagues Prof. Dr. Gert Pfurtscheller, Prof. Dr. Christa Neuper, Prof. Dr. Ken Hunt, Prof. Birbaumer and Dr. Alexa Riehle, for their support during the project proposal writing and for the generous hosting of Dr. Ivan Volosyak. I would also like to thank Prof. Dr. Petko Kiriazov, Dr. Piotr Durka, Dr. Maciej Pokora and Dr. Henrik Gollee for accepting the invitation to visit IAT and for sharing their knowledge with us. The experienced incoming scientists Dr. Ola Friman, Dr. Bernhard Graimann, Dr. Brendan Allison, Dr. Hubert Cecotti (ordered according to time of arrival at the IAT) as well as Dr. Ivan Volosyak, Dipl.-Ing. Diana Valbuena, Dipl.-Ing. Thorsten Lüth, M.Sc. Aavo Moltsaar and Dipl.-Ing. Amir Teymourian (all five from the IAT) also made important contributions to the success of the TOK project. I thank all of them for their dedication to BRAINROBOT. Last but not least I would like to thank the EU project officers Dr. Marcela Groholova and Laura Elena Apostol for their advice and support and the patient help to solve several organizational problems during the execution of the project. Finally, I hope that the readers will enjoy reading the different chapters in this booklet.

Bremen, February 2010

Axel Gräser  
Project Coordinator BRAINROBOT

# Contents

<b>Preface</b>	<b>3</b>
<b>I. Introduction</b>	<b>9</b>
<b>1. Non-invasive Brain-Computer Interfaces</b>	<b>11</b>
1.1. BCI Components . . . . .	11
1.2. SSVEP-based BCI . . . . .	14
1.3. P300-based BCI . . . . .	15
1.4. SMR-based BCI . . . . .	16
<b>II. Advanced Signal Processing</b>	<b>17</b>
<b>2. Signal Processing for BCIs and Scientific Computing</b>	<b>19</b>
2.1. Spectral Filters . . . . .	19
2.2. Spatial Filtering . . . . .	20
2.3. Classification . . . . .	21
2.4. Scientific Computing . . . . .	21
<b>3. Eye Artifact Reduction with ICA and Regression</b>	<b>27</b>
3.1. Introduction . . . . .	27
3.2. Signal Processing Methods . . . . .	29
3.3. Experimental Setup and Comparison Procedure . . . . .	32
3.4. Pertinence and Implementation . . . . .	34
3.5. Description and Examples of Recorded Data . . . . .	37
3.6. Results . . . . .	37
3.7. Discussion and Conclusion . . . . .	39
<b>4. Multiple Channel Detection of SSVEP</b>	<b>45</b>
4.1. Introduction . . . . .	45
4.2. Modeling . . . . .	46
4.3. Methods . . . . .	47
4.4. Material . . . . .	52
4.5. Results . . . . .	52
4.6. Discussion . . . . .	56
4.7. Conclusions . . . . .	57
<b>5. Auto-regressive Approach for Noise Reduction</b>	<b>61</b>

5.1. Introduction . . . . .	61
5.2. Parametric Power Spectrum Estimation . . . . .	61
5.3. Fitting $AR(p)$ Models to the Channel Signals . . . . .	62
5.4. Choosing the Optimal Model Order . . . . .	63
5.5. Conclusion . . . . .	67
<b>6. SSVEP Detection with Neural Networks</b>	<b>69</b>
6.1. Introduction . . . . .	69
6.2. SSVEP Response . . . . .	70
6.3. Channel Creation . . . . .	70
6.4. Classifier Overview . . . . .	71
6.5. Methods . . . . .	77
6.6. Results . . . . .	80
6.7. Conclusion . . . . .	87
<b>7. P300 Detection with Neural Networks</b>	<b>89</b>
7.1. Convolutional Neural Network . . . . .	89
7.2. Input Normalization . . . . .	89
7.3. Neural Network Topology . . . . .	90
7.4. Learning . . . . .	91
7.5. Classifiers . . . . .	92
7.6. Database . . . . .	93
7.7. Results . . . . .	94
7.8. Conclusion . . . . .	100
<b>8. Asynchronous Motor Imagery-based Brain Switch</b>	<b>103</b>
8.1. Introduction and Physiological Background . . . . .	103
8.2. Methods . . . . .	104
8.3. Results . . . . .	106
8.4. Conclusions . . . . .	107
<b>9. Selection of Reactive Frequency Bands during Motor Imagery</b>	<b>109</b>
9.1. Introduction . . . . .	109
9.2. Motor Imagery . . . . .	109
9.3. EEG Signal Acquisition . . . . .	110
9.4. ERD/ERS Calculation . . . . .	112
9.5. Results . . . . .	114
9.6. Conclusion . . . . .	116
<b>III. Hardware Development</b>	<b>117</b>
<b>10. LED Stimulator</b>	<b>119</b>
10.1. Introduction . . . . .	119
10.2. LED Controller . . . . .	120
10.3. Electrical Connections . . . . .	120
10.4. Programming the Controller . . . . .	120



<b>11. Wearable SSVEP Stimulator</b>	<b>125</b>
11.1. Introduction	125
11.2. Hardware Description	126
11.3. Tests and Results	127
 <b>IV. Software Development</b>	 <b>131</b>
<b>12. Spelling with SSVEP</b>	<b>133</b>
12.1. Introduction	133
12.2. Letter Selection	133
12.3. Preliminary Tests	134
12.4. Cursor-based Layouts	136
12.5. Cursor-based vs. Row-Column	137
 <b>13. Speller with Integrated SSVEP Stimulator</b>	 <b>139</b>
13.1. Introduction	139
13.2. Spelling Layout	140
13.3. Visual Stimulator	140
13.4. Software Architecture	142
13.5. Conclusion	144
 <b>14. Reliable Stimuli on LCD Screen</b>	 <b>147</b>
14.1. Introduction	147
14.2. Stimuli on an LCD Screen	148
14.3. Evaluation Methods	151
14.4. EEG Classification	152
14.5. Experimental Protocol	153
14.6. Results	155
14.7. Conclusion	157
 <b>V. Applications in Robotics and Rehabilitation</b>	 <b>159</b>
<b>15. Control of a Semi-autonomous Rehabilitation Robotic System via BCI</b>	<b>161</b>
15.1. Introduction	161
15.2. Multi-layer Architecture	162
15.3. SSVEP-based BCI	166
15.4. High-level Control	167
15.5. Low-level Control	169
15.6. Conclusion	174
 <b>16. BCI driven Wheelchairs</b>	 <b>177</b>
16.1. Introduction	177
16.2. Low-level Control	177
16.3. State-machine Control	178
16.4. Semi-autonomous Control	181

<b>17. BCI to Improve Respiratory Function</b>	<b>185</b>
17.1. Introduction . . . . .	185
17.2. Materials and Methods . . . . .	187
17.3. Results . . . . .	194
17.4. Discussion . . . . .	195
17.5. Conclusions and Future Work . . . . .	198
 <b>VI. Demonstrations at International Fairs</b>	 <b>201</b>
 <b>18. CeBIT 2008</b>	 <b>203</b>
18.1. Introduction . . . . .	203
18.2. Methods and Materials . . . . .	205
18.3. Results . . . . .	208
18.4. Discussion . . . . .	208
18.5. Future Directions . . . . .	214
 <b>19. RehaCare 2008</b>	 <b>215</b>
19.1. Introduction . . . . .	215
19.2. Experiments . . . . .	215
19.3. Results . . . . .	220
19.4. Discussion . . . . .	228
19.5. Conclusions . . . . .	229
 <b>Bibliography</b>	 <b>231</b>