

# Adaptronics and Smart Structures

Hartmut Janocha (Editor)

---

# Adaptronics and Smart Structures

Basics, Materials, Design and Applications

Second, Revised Edition

With 432 Figures and 17 Tables

 Springer

Prof. Dr.-Ing. habil. Hartmut Janocha  
Universität des Saarlandes  
Lehrstuhl für Prozessautomatisierung  
Gebäude A5 1  
66123 Saarbrücken  
Germany  
E-mail: janocha@lpa.uni-saarland.de

Library of Congress Control Number: 2007925681

ISBN 978-3-540-71965-6 2nd Edition Springer Berlin Heidelberg New York  
ISBN 978-3-540-61484-5 1st Edition Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media  
springer.com

© Springer-Verlag Berlin Heidelberg 1999, 2007

The use of general descriptive names, registered names, trademarks, 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.

Typesetting and production: LE- $\text{\TeX}$  Jelonek, Schmidt & Vöckler GbR, Leipzig  
Cover: WMXDesign GmbH, Heidelberg

SPIN 12044214 57/3180/YL - 5 4 3 2 1 0 Printed on acid-free paper

# Preface to the 2nd Book Edition

The coined word *adaptronics* describes technical fields that have become known internationally under the names smart materials, smart structures or intelligent systems. The term adaptronics was originally formulated by the limited liability company VDI-Technologiezentrum in Düsseldorf, Germany. In the autumn of 1991 the term was sanctioned by a board of independent experts. Initially, the term encompassed all functions of traditional control loops, which are applied to generate adaptive behaviour, i. e. adaptronic systems or structures that adapt automatically to different operating and environmental conditions. Furthermore, in contrast to conventional control loops in which each functional element is a separate component, adaptronics is characterised by multi-functional components. Thus, several application-specific functional elements are embodied in one single component (e. g. a self-sensing actuator), which is preferably integrated into the structure or the system. The intention is to build lightweight adaptive systems and structures to be as simple as possible, with the ultimate goal of reducing the material and energy resources needed for implementation and operation to an absolute minimum.

Given this background it is obvious that apart from the technical requirements for automation, modern functional materials are an essential basis for the successful design and application of adaptronic products. Today, the most well known of these materials are shape-memory alloys, magnetorheological fluids and piezoelectric materials. An old example of an adaptronic product that has been cited numerously are glasses made of photochromic glass. These glasses automatically change the light transmission depending on the surrounding light intensity by performing sensor, actuator and closed-loop control functions for transmission adaptation. Looking to other technical areas, adaptronics has great potential for application in vibration and noise reduction. Fields of application include, for instance, the automotive industry, mechanical engineering, architecture as well as the aerospace industry. Other kinds of application scenarios focus on nature trying to simulate fundamental ‘vital functions’ by means of adaptronics. One aspect is the ability of biological systems to recognise and automatically correct local disfunctions in their structure. Naturally, this feature is also desirable for technical systems and structures, especially in areas where safety is essential (civil structures, aircraft).

With this book the editor and the publisher have tackled the task of presenting the state of the art of this both fascinating and demanding technological-scientific field. In this 2nd. book edition the contents from the 1st. edition from 1999 have been updated and extended corresponding to the development progress. The outline, which has proven worthwhile, has been maintained: following an introduction describing the aims and the content of adaptronics, subsequent chapters present the ‘scientific pillars’ from the viewpoint of the various basic disciplines involved. Thereafter, important components of adaptronic structures and systems, such as actuators and sensors, are described. The remaining chapters are dedicated to applications of adaptronics in the various technological and biological/medical fields of daily life, and an outlook towards future developments concludes the book.

It is obvious that no one single person can master all the specialist knowledge involved in such a detailed and varied field as adaptronics. Thus, we recognize both a necessity and a great opportunity in bringing together, in a fundamental work, the knowledge and the experience of proven experts from across the range of adaptronic disciplines. The editor is proud of the fact that numerous experts from all over the world have supported him in performing this task. To all of these he expresses his gratitude. It will not escape the attention of the reader that, in their nuances, viewpoints about adaptronics may diverge somewhat. However, this situation is actually both attractive and stimulating. It is also hardly surprising in view of the fact that adaptronics has only begun a few years ago, to establish itself as a discipline in its own right.

With this background in mind, the editor and publisher hope that the 2nd. edition of this book will also become a useful source of information and ideas, which a large number of readers can rely on time and again. Perhaps it will help some readers to discover their interest or their vocation to actively and creatively support the field of adaptronics along its path to maturity.

Finally, the editor would like to thank his co-workers Petra Detemple, Chris May and Andreas Biehl for their untiring help in transferring the manuscripts and figures, which the contributing authors had presented in widely varied forms, into a uniform format. He also thanks the publishing house Springer-Verlag for the appealing outward design of the book.

In conclusion, the editor wants to assure the critical readership that its constructive comments about the conception, content and presentation of this book are welcome and will be taken into consideration, if possible, in future editions.

Saarbrücken, Germany  
Juli 2007

*Hartmut Janocha*

# Contents

## 1 Adaptronics:

### A Concept for the Development of Adaptive and Multifunctional Structures

<i>D. Neumann</i> .....	1
1.1 What is Adaptronics? .....	1
1.2 Examples of Adaptronic Systems .....	1
1.3 Multifunctional Elements .....	4
1.4 Fields of Technology and Application .....	4
1.5 Historical Review .....	6
References .....	8

## 2 Concepts of Adaptronic Structures

<i>V. Giurgiutiu</i> .....	9
2.1 What are Adaptronic Structures? .....	9
2.2 Construction of Adaptronic Structures .....	12
2.2.1 Artificial Muscles: Actuators .....	13
2.2.2 Artificial Nerves: Sensors .....	14
2.2.3 Intelligence: Signal Processing, Communication, and Controls .....	16
2.2.4 Adaptive Algorithms for Smart Structures Control .....	17
2.3 Application Examples .....	18
2.3.1 Solid State Actuation and Morphing Structures .....	18
2.3.2 Structural Health Monitoring and Self-Repairing Structures .....	22
2.4 Future Adaptronic Structures .....	26
References .....	27

## 3 Multifunctional Materials:

### The Basis for Adaptronics

<i>W. Cao</i> .....	29
3.1 What are Functional Materials? .....	29
3.2 Basic Principles of Functional Materials .....	30
3.2.1 Phase Transitions and Anomalies .....	31
3.2.2 Microscopic, Mesoscopic, Macroscopic Phenomena and Symmetries .....	33

3.2.3	Energy Conversion . . . . .	37
3.3	Examples of Functional Materials . . . . .	40
3.3.1	Thermal Responsive Materials . . . . .	40
3.3.2	Materials Responsive to Electric, Magnetic and Stress Fields . . . . .	42
3.4	Increased Functionality Through Material Engineering . . . . .	45
3.4.1	Morphotropic Phase Boundary . . . . .	46
3.4.2	Domain Engineering . . . . .	48
3.4.3	Functional Composites . . . . .	49
3.5	Summary . . . . .	51
	References . . . . .	52
<b>4 Controllers in Adaptronics</b>		
	<i>V. Rao, R. Damle, S. Sana</i> . . . . .	55
4.1	Introduction . . . . .	55
4.2	Description of the Test Articles . . . . .	57
4.3	Conventional Model-Reference Adaptive Control Techniques . . . . .	58
4.3.1	Experimental Results . . . . .	59
4.4	Adaptive Control Using Neural Networks . . . . .	61
4.4.1	Neural Network-Based Model Reference Adaptive Control . . . . .	61
4.4.2	Neural Network-Based Optimizing Controller With On-Line Adaptation . . . . .	65
4.5	Robust Controllers for Structural Systems . . . . .	69
4.5.1	Uncertainty Modeling . . . . .	70
4.5.2	Robust Control Design Methods . . . . .	71
4.6	Summary . . . . .	72
	References . . . . .	73
<b>5 Simulation of Adaptronic Systems</b>		
	<i>H. Baier, F. Döngi, U. Müller</i> . . . . .	75
5.1	Introduction . . . . .	75
5.2	Related Elements of System Theory . . . . .	75
5.2.1	Linear and Nonlinear Systems . . . . .	75
5.2.2	State-Space Representation . . . . .	76
5.2.3	Controllability and Observability . . . . .	77
5.2.4	Stability . . . . .	78
5.2.5	Alternative System Representations . . . . .	78
5.3	Modelling of Adaptronic Structures . . . . .	79
5.3.1	Basic Equations of Structural Mechanics . . . . .	79
5.3.2	Constitutive Laws of Smart Materials . . . . .	80
5.3.3	Finite Element Modelling . . . . .	81
5.3.4	Equations of Motion . . . . .	82
5.3.5	Sensor Equations . . . . .	83
5.3.6	Model Reduction Techniques . . . . .	83

5.4	Analysis of Adaptronic Systems and Structures . . . . .	84
5.4.1	Stability Analysis . . . . .	84
5.4.2	Spillover . . . . .	85
5.4.3	Numerical Time Integration . . . . .	85
5.5	Application Example . . . . .	86
5.6	Optimization of Adaptronic Systems . . . . .	89
5.6.1	Problem Statements . . . . .	89
5.6.2	Solution Techniques . . . . .	90
5.7	Software Tools for Adaptronic Structure Simulation . . . . .	91
5.7.1	Solution Techniques . . . . .	91
5.7.2	Control Design and Simulation Tools . . . . .	91
5.7.3	System Identification Tools . . . . .	92
	References . . . . .	92

**6 Actuators in Adaptronics**

6.1	The Role of Actuators in Adaptronic Systems	
	<i>H. Janocha</i> . . . . .	95
6.1.1	What is an Actuator? . . . . .	95
6.1.2	Actuator as a System Component . . . . .	97
6.1.3	Power Electronics . . . . .	100
6.1.4	‘Intelligent’ and Self-Sensing Actuators . . . . .	101
6.1.5	Actuator Design . . . . .	104
6.2	Piezoelectric Actuators	
	<i>R. Leletty, F. Claeysen</i> . . . . .	107
6.2.1	Physical Effect . . . . .	107
6.2.2	Materials . . . . .	108
6.2.3	Design of Piezoelectric Transducers . . . . .	111
6.2.4	Piezoelectric Transducer With Displacement Amplification . . . . .	114
6.2.5	Piezoelectric Motors . . . . .	115
6.2.6	Limitations of Piezoelectric Actuators . . . . .	118
6.2.7	Example Applications of Piezoelectric Actuator Used in Adaptronics . . . . .	119
6.2.8	Energy Harvesting Application Using Piezoelectric Actuators . . . . .	124
6.2.9	Outlook . . . . .	124
6.3	Magnetostrictive Actuators	
	<i>F. Claeysen, G. Engdahl</i> . . . . .	126
6.3.1	Theory of Magnetostriction in Magnetostrictive Devices . . . . .	127
6.3.2	Principles and Properties of Various Applications . . . . .	135
6.3.3	Summary . . . . .	145
6.3.4	Acknowledgement . . . . .	145
6.4	Shape Memory Actuators	
	<i>J. Hesselbach</i> . . . . .	145



6.4.1	Properties of Shape Memory Alloys .....	146
6.4.2	Electrical Shape Memory Actuators .....	152
6.4.3	Perspectives for Shape Memory Actuators.....	157
6.4.4	Innovative Application Examples.....	159
6.4.5	Conclusion .....	163
6.5	Electrorheological Fluid Actuators	
	<i>W.A. Bullough</i> .....	163
6.5.1	Particulate Fluids .....	163
6.5.2	Limitations to the Concept of Particulate Electrorheological Fluids .....	174
6.5.3	Future Aims and Present Problems.....	180
6.5.4	Summary of Advantages of Particulate ER Fluids .....	182
6.5.5	Homogenous ERF.....	182
6.5.6	Other ER Fluids .....	183
6.6	Magnetorheological Fluid Actuators	
	<i>J.D. Carlson</i> .....	184
6.6.1	Description of MR Fluids .....	185
6.6.2	Advantages and Concerns .....	186
6.6.3	MR Fluid Devices .....	189
6.6.4	Basic MR Device Design Considerations .....	192
6.6.5	Examples of MR Devices and Systems .....	196
6.6.6	Conclusion .....	204
6.7	Electroactive Polymer Actuators	
	<i>A. Mazzoldi, F. Carpi, D. De Rossi</i> .....	204
6.7.1	Introduction.....	204
6.7.2	Polyelectrolyte Gels (PG) .....	205
6.7.3	Ion-Polymer Metal Composites (IPMC) .....	208
6.7.4	Conducting Polymers (CP).....	210
6.7.5	Carbon Nanotubes (CNT) .....	216
6.7.6	Dielectric Elastomers (DE) .....	217
6.7.7	Electroactive Polymers as Sensors .....	220
6.7.8	Final Remarks and Conclusions .....	224
6.8	Microactuators	
	<i>H. Seidel</i> .....	225
6.8.1	Introduction.....	225
6.8.2	Driving Mechanisms, Scaling Laws, and Materials .....	226
6.8.3	Microfluidic Systems and Components .....	232
6.8.4	Actuators in Microoptical Systems .....	239
6.8.5	Microdrives .....	241
6.8.6	Conclusion and Outlook .....	244
6.9	Self-Sensing Solid-State Actuators	
	<i>H. Janocha, K. Kuhnen</i> .....	245
6.9.1	Introduction.....	245
6.9.2	Solid-State Actuators.....	247

6.9.3 Self-Sensing Model for Solid-State Actuators . . . . . 252

6.9.4 Concept of Self-Sensing Solid-State Actuators . . . . . 254

6.9.5 Modeling Hierarchy of Self-Sensing Actuators . . . . . 257

6.9.6 Application Example:  
1-DOF Piezoelectric Positioning System . . . . . 262

6.9.7 Conclusion . . . . . 265

6.10 Power Amplifiers for Unconventional Actuators  
*H. Janocha, T. Würtz* . . . . . 265

6.10.1 General Information About Power Electronics . . . . . 266

6.10.2 Power Electronics for Piezo Actuators  
and Actuators with Electrorheological Fluids . . . . . 273

6.10.3 Power Electronics for Magnetostrictive Actuators  
and Actuators with Magnetorheological Fluids . . . . . 279

6.10.4 How to Proceed When Choosing an Amplifier Concept 280

References . . . . . 282

**7 Sensors in Adaptronics**

7.1 Advances in Intelligent Sensors  
*N.M. White, P. Boltryk* . . . . . 301

7.1.1 Introduction . . . . . 301

7.1.2 Primary Sensor Defects . . . . . 302

7.1.3 Hardware Structures . . . . . 304

7.1.4 Software Processes . . . . . 307

7.1.5 Case in Point: Load Cell . . . . . 311

7.1.6 The Impact of ASICs . . . . . 312

7.1.7 Reconfigurable Systems . . . . . 313

7.1.8 Communications . . . . . 315

7.1.9 Trends . . . . . 318

7.2 Fiber Optic Sensors  
*W.R. Habel* . . . . . 319

7.2.1 Introduction . . . . . 319

7.2.2 Basic Principle of Operation . . . . . 320

7.2.3 Commonly Used Sensor Types  
for Deformation Measurement . . . . . 322

7.2.4 Fiber Sensors for Physical and Chemical Parameters . . 332

7.2.5 Particular Aspects of Sensor Application . . . . . 333

7.2.6 Application Examples . . . . . 335

7.2.7 Research Tasks and Future Prospects . . . . . 341

7.3 Piezoelectric Sensors  
*R. Petricevic, M. Gurka* . . . . . 342

7.3.1 Introduction . . . . . 342

7.3.2 Sensor Relevant Physical Quantities . . . . . 344

7.3.3 Materials and Designs . . . . . 347

7.3.4 Passive and Active Piezo Sensors . . . . . 354

7.3.5 Piezo Sensors as Integral Components of Structures . . 360

7.3.6	Sensory Structures . . . . .	361
7.3.7	Adaptive Structures . . . . .	362
	References . . . . .	364

**8 Adaptronic Systems in Engineering**

8.1	Adaptronic Systems in Aeronautics and Space Travel	
	<i>C. Boller</i> . . . . .	371
8.1.1	Implications and Initiatives . . . . .	371
8.1.2	Structural Health Monitoring . . . . .	374
8.1.3	Shape Control and Active Flow . . . . .	377
8.1.4	Damping of Vibration and Noise . . . . .	385
8.1.5	Smart Skins . . . . .	391
8.1.6	Control . . . . .	392
8.1.7	Systems . . . . .	392
8.2	Adaptronic Systems in Automobiles	
	<i>T. Melz, D. Mayer, M. Thomaier</i> . . . . .	394
8.2.1	Preamble . . . . .	394
8.2.2	AVC/ASAC Project Examples . . . . .	396
8.2.3	Current Research Topics for Automotive Smart Structures . . . . .	403
8.2.4	Summary and Outlook . . . . .	408
8.3	Adaptronic Systems in Machine and Plant Construction	
	<i>H. Janocha</i> . . . . .	412
8.3.1	Grinding Machines . . . . .	413
8.3.2	Milling and Turning Machines . . . . .	417
8.3.3	Deep Drilling Tools . . . . .	422
8.3.4	Adaptronic Machine Components . . . . .	423
8.3.5	Conclusion . . . . .	428
8.4	Adaptronics in Civil Engineering Structures	
	<i>G. Hirsch</i> . . . . .	428
8.4.1	State of the Art for Active Control of Civil Engineering Structures . . . . .	430
8.4.2	The Second Generation of Active Control . . . . .	436
8.4.3	Application of Active Control from Practical Engineering Aspects . . . . .	437
8.4.4	Results of Experimental and Full-Scale Tests (in Japan and the U.S.) . . . . .	438
8.4.5	Conclusions . . . . .	442
8.5	Adaptronic Vibration Absorbers for Ropeway Gondolas	
	<i>H. Matsuhisa</i> . . . . .	443
8.5.1	Dynamic Vibration Absorbers . . . . .	444
8.5.2	Dynamic Vibration Absorbers for Gondola . . . . .	446
8.5.3	Gyroscopic Moment Absorber for Gondola . . . . .	452
8.5.4	Conclusions and Outlook on Future Research . . . . .	456
	References . . . . .	456

**9 Adaptronic Systems in Biology and Medicine**

9.1 The Muscle as a Biological Universal Actuator in the Animal Kingdom  
*W. Nachtigall* ..... 469

9.1.1 Principles of Construction and Function ..... 470

9.1.2 Analogies to Muscle Function and Fine Structure ..... 472

9.1.3 Muscle Contraction ..... 473

9.1.4 Aspects of Muscle Mechanics ..... 476

9.1.5 Principal Types of Motion Achievable by a Muscle and its Antagonists ..... 479

9.1.6 Force and Position of Muscular Levers ..... 482

9.1.7 Cooperation of Unequal Actuators ..... 484

9.1.8 Muscles as Actuators in Controlled Systems ..... 486

9.1.9 Control Loops in Biology: Similarities Within Biology and Engineering ..... 490

9.2 Adaptronic Systems in Medicine and Medical Technology  
*J.-U. Meyer, T. Stieglitz* ..... 491

9.2.1 Introduction ..... 491

9.2.2 Adaptive Implants ..... 493

9.2.3 Adaptive Diagnostic Systems ..... 500

9.2.4 Conclusions and Outlook ..... 502

References ..... 503

**10 Future Perspectives: Opportunities, Risks and Requirements in Adaptronics**

*B. Culshaw* ..... 507

10.1 What's in a Name? ..... 507

10.2 Where Could Adaptronics Contribute: the Future? ..... 510

10.3 But it is More Than Technology ..... 512

10.4 Educating the Public ..... 514

10.5 The International Dimension:  
 And Musings on Technology Transfer ..... 515

10.6 And What About Technology? ..... 516

10.7 Some Concluding Thoughts ..... 517

**Index** ..... 521

**About the Authors** ..... 535

# List of Contributors

## **Horst Baier**

Institute of Lightweight Structures,  
Aerospace Department,  
Faculty of Mechanical Engineering,  
Technische Universität München  
baier@llb.mw.tum.de

## **Christian Boller**

The University of Sheffield,  
Department of Mechanical  
Engineering, Mappin Street,  
Sheffield S1 3JD,  
United Kingdom  
c.boller@sheffield.ac.uk

## **Peter Boltryk**

School of Engineering Sciences,  
University of Southampton,  
Southampton, SO17 1BJ, UK  
boltryk@soton.ac.uk

## **William A. Bullough**

Prof. William A. Bullough, Department  
of Mechanical Engineering,  
The University of Sheffield, Mappin  
Street, Sheffield, S1 3JD, UK.  
Hoodgreen7@aol.com

## **Wenwu Cao**

Department of Mathematics,  
The Pennsylvania State University,  
339 McAllister Bldg.,  
University Park, PA 16802, USA  
cao@math.psu.edu

## **J. David Carlson**

LORD Corporation,  
406 Gregson Drive,  
Cary, NC 27511-6445, USA  
jcarlson@lord.com

## **Federico Carpi**

Interdepartmental Research Centre  
E. Piaggio,  
Faculty of Engineering,  
University of Pisa,  
Via Diotisalvi 2, 56126 Pisa, Italy  
f.carpi@ing.unipi.it

## **Frank Claeysen**

CEDRAT Technologies, Zirst,  
F38246 Meylan Cedex, France  
Frank.Claeysen@cedrat.com

## **Brian Culshaw**

University of Strathclyde,  
Department of Electronic  
& Electrical Engineering,  
204 George Street,  
Glasgow G1 1XW  
bc@eee.strath.ac.uk

## **Frank Döngi**

EADS Astrium SAS,  
31, rue des Cosmonautes,  
31402 Toulouse Cedex 4, France  
frank.doengi@astrium.eads.net

## **Goran Engdahl**

Cedrat Recherche, Zirst,  
F38246 Meylan Cedex, France  
goran.engdahl@ekc.kth.se

**Victor Giurgiutiu**

Department of Mechanical Engineering, University of South Carolina Columbia, SC 29208, USA  
giurgiut@engr.sc.edu

**Martin Gurka**

Neue Materialien Würzburg GmbH, Friedrich Bergius Ring 22a, 97076 Würzburg, Germany  
gurka@nmwgmbh.de

**Wolfgang R. Habel**

Bundesanstalt für Materialforschung und -prüfung (BAM), Fachgruppe VIII.1: Mess- und Prüftechnik, Sensorik, Leiter der Arbeitsgruppe "Faseroptische Sensorik", Unter den Eichen 87, 12205 Berlin, Germany  
wolfgang.habel@bam.de

**Jürgen Hesselbach**

TU Braunschweig, Institut für Werkzeugmaschinen und Fertigungstechnik, Langer Kamp 19b, 38106 Braunschweig  
j.hesselbach@tu-bs.de

**Hartmut Janocha**

Universität des Saarlandes, Lehrstuhl für Prozessautomatisierung, Gebäude A5 1, D-66123 Saarbrücken, Germany  
janocha@lpa.uni-saarland.de

**Klaus Kuhnen**

Universität des Saarlandes, Lehrstuhl für Prozessautomatisierung, Gebäude A5 1, D-66123 Saarbrücken, Germany  
k.kuhnen@lpa.uni-saarland.de

**Ronan Leletty**

CEDRAT Technologies, Zirst, F38246 Meylan Cedex, France  
Ronan.Leletty@cedrat.com

**Hiroshi Matsuhisa**

Dept. of Mechanical Engineering, Kyoto University, Kyoto, 520-8501, Japan  
matsu@me.kyoto-u.ac.jp

**Dirk Mayer**

Fraunhofer Institute for Structural Durability and System Reliability, Department of Mechatronics/Adaptronics, Bartningstr. 47, Post Office Box 100545, 64289 Darmstadt, Germany  
dirk.mayer@lbf.fhg.de

**Tobias Melz**

Fraunhofer Institute for Structural Durability and System Reliability, Department of Mechatronics/Adaptronics, Bartningstr. 47, Post Office Box 100545, 64289 Darmstadt, Germany  
tobias.melz@lbf.fraunhofer.de

**Jörg-Uwe Meyer**

Head of Research, Drägerwerk AG, Moislinger Allee 53-55, D-23542 Lübeck, Germany  
joerg-uwe.meyer@draeger.com

**Uwe Müller**

Institute of Lightweight Structures, Aerospace Department, Faculty of Mechanical Engineering, Technische Universität München  
umueller@l1b.mw.tum.de

**Werner Nachtigall**

Prof. Dr. rer. nat. Werner Nachtigall,  
Zoologie, Universität  
des Saarlandes, Gebäude A2 4,  
66041 Saarbrücken, Germany.  
gtbb@mx.uni-saarland.de

**Dieter Neumann**

Acteos GmbH & Co. KG,  
Talhofstr. 30a, 82205 Gilching,  
Germany  
dieter.neumann@acteos.de

**Raino Petricevic**

Neue Materialien Würzburg GmbH,  
Friedrich Bergius Ring 22a,  
97076 Würzburg, Germany  
petricevic@nmwgmbh.de

**Danilo De Rossi**

Interdepartmental Research Centre  
E. Piaggio,  
Faculty of Engineering,  
University of Pisa,  
Via Diotisalvi 2, 56126 Pisa, Italy  
d.derossi@ing.unipi.it

**Helmut Seidel**

University of Saarland,  
Institute for Micromechanics,  
Microfluidics/Microactuators,  
University Campus, Building A5 1,  
P.O. Box 151150,  
D-66041 Saarbrücken, Germany  
seidel@lmm.uni-saarland.de

**Thomas Stieglitz**

Laboratory for Biomedical  
Microtechnology, Department of  
Microsystems Engineering,  
University of Freiburg IMTEK,  
Georges-Köhler-Allee 102,  
D-79110 Freiburg, Germany  
stieglitz@imtek.de

**Martin Thomaier**

Fraunhofer Institute for  
Structural Durability  
and System Reliability,  
Department of Mechatronics/  
Adaptronics,  
Bartningstr. 47,  
Post Office Box 100545,  
64289 Darmstadt, Germany  
martin.thomaier@lbf.fhg.de

**Neil M. White**

School of Electronics  
and Computer Science,  
University of Southampton,  
Highfield, Southampton, SO17 1BJ,  
UK  
nmw@ecs.soton.ac.uk

**Thomas Würtz**

Universität des Saarlandes,  
Lehrstuhl für  
Prozessautomatisierung,  
Gebäude A5 1,  
D-66123 Saarbrücken, Germany  
tw@zip.uni-sb.de