Self-Organization, Embodiment, and Biologically Inspired Robotics

Rolf Pfeifer, Max Lungarella, Fumiya Lida
Science, 318, 1088-1093 (2007 Nov)
## Original Research

<table>
<thead>
<tr>
<th>Type</th>
<th>Words</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Article</td>
<td><del>4500 (</del> 5 pages)</td>
<td>Major Advance</td>
</tr>
<tr>
<td>Reports</td>
<td>~2500 (~3 pages)</td>
<td>Important New Research Results of Broad Significance</td>
</tr>
<tr>
<td>Brevia</td>
<td>600~800</td>
<td>Brief Contribution</td>
</tr>
<tr>
<td>Reviews</td>
<td>~3500</td>
<td>New developments of interdisciplinary significance and highlight future directions</td>
</tr>
</tbody>
</table>
# Commentary

<table>
<thead>
<tr>
<th>Category</th>
<th>Words</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perspectives</td>
<td>~1000 words</td>
<td>Highlight recent exciting research</td>
</tr>
<tr>
<td>Books et al.</td>
<td>1000 words</td>
<td>Reviews of current books, multimedia, exhibitions, and films</td>
</tr>
<tr>
<td>Policy Forum</td>
<td>1000~2000 words</td>
<td>Policy implications</td>
</tr>
<tr>
<td>Education Forum</td>
<td>~2000 words</td>
<td>Science education</td>
</tr>
<tr>
<td>Letters</td>
<td>~300</td>
<td>Discuss material published in Science in the last 3 months</td>
</tr>
</tbody>
</table>
Review Process

- Paper → Staff Editor
- → Rated for Suitability by members of Science’s Board of Reviewing Editors
- → If not highly rated → Notification within about 1 to 2 weeks
- → Selected for In-Depth Review → At least two outside referees
  - → Comments within 1 to 2 weeks
Review Boards (Computation?)

- Wulfram Gerstner (EPFL) : Computational Neuroscience
- James A. Hendler (RPI) : Computer Science and Cognitive Science
- Michael J. Sanderson (U. of Arizona) : Computational Biology
Science Contributor’s FAQ

- Acceptance Rate: 8% of the original research papers submitted
- About 80% of submitted manuscripts are rejected during the initial screening stage (within one week to 10 days)
Robotics

CONTENTS

News
1084 Making Machines That Make Others of Their Kind
1086 Robots' Allure: Can It Remedy What Ails Computer Science?

Reviews
1088 Self-Organization, Embodiment, and Biologically Inspired Robotics
R. Pfeifer, M. Lungarella, F. iida
1094 Mobile Robots: Motor Challenges and Materials Solutions
J. D. Madden
1098 Robotics in Remote and Hostile Environments
J. G. Bellingham and K. Rajan

Perspective
1102 Learning in and from Brain-Based Devices
G. M. Edelman

See also related Editorial page 1037; News stories by Pennisi, Service, and Cho; Report page 1155; and online material page 1031 or at http://www.sciencemag.org/sciext/robotics
Special Issues (2010)

- 19 February 2010: 2009 Visualization Challenge
- 12 February 2010: Food Security
- 15 January 2010: Innate Immunity
Special Issues (2009)

- 18 December 2009: Breakthrough of the Year
- 16 October 2009: Neuroscience Methods
- 1 October 2009: Ardipithecus ramidus
- 25 September 2009: Carbon Capture and Sequestration
- 7 August 2009: Industrial Chemistry
- 31 July 2009: Restoration Ecology
- 24 July 2009: Complex Systems and Networks
- 26 June 2009: Stem Cells
- 8 May 2009: Plant-Microbe Interactions
- 10 April 2009: Protein Dynamics
- 6 February 2009: Speciation
- 9 January 2009: Origins
- 2 January 2009: Education & Technology
Special Issues (2008)

- 19 December 2008: Breakthrough of the Year
- 5 December 2008: Organ Development
- 7 November 2008: Genetics of Behavior
- 17 October 2008: Cell Signaling
- 10 October 2008: Clinical Trials and Tribulations
- 8 August 2008: Theoretical Chemistry
- 18 July 2008: Drug Resistance
- 4 July 2008: MESSENGER
- 13 June 2008: Forests in Flux
- 23 May 2008: Microbial Ecology
- 25 April 2008: Plant Genomes
- 28 March 2008: Gene Regulation
- 29 February 2008: Quantum Matter
- 8 February 2008: Cities
- 4 January 2008: The Cosmic Web
Special Issues (2007)

- 21 December 2007: Breakthrough of the Year
- 7 December 2007: Hinode
- 30 November 2007: The Nucleus
- 16 November 2007: Robotics
- 26 October 2007: Decision-Making
- 12 October 2007: New Horizons at Jupiter
- 5 October 2007: Cell Signaling
- 21 September 2007: Mars Reconnaissance Orbiter
- 7 September 2007: Social Cognition
- 10 August 2007: Attosecond Spectroscopy
- 3 August 2007: Challenges in Immunology
- 6 July 2007: The World of Undergraduate Education
- 25 May 2007: Single Molecules
- 18 May 2007: Behavioral Science
- 20 April 2007: Germ Cells
- 13 April 2007: The Macaque Genome
- 16 March 2007: Polar Science
- 9 February 2007: Sustainability and Energy
- 5 January 2007: Particle Astrophysics
Authors

- Rolf Pfeifer\textsuperscript{1}, Max Lungarella\textsuperscript{1}, Fumiya Lida\textsuperscript{1,2}
- \textsuperscript{1}Department of Informatics, Artificial Intelligence Laboratory, University of Zurich, Switzerland
- \textsuperscript{2}Computer Science and Artificial Intelligence Laboratory, MIT
how the body shapes the way we think

a new view of intelligence

foreword by Rodney Brooks

Rolf Pfeifer and Josh Bongard
Biological Organisms

Rapid Changes

High Uncertainty

Indefinite Richness

Limited Availability of Information

http://www.kingsnake.com/westindian/diaprepesabbreviatus2.JPG
Industrial Robots

Bio-Inspired Robotics

Adaptivity
Robustness
Versatility
Agility

http://www.rdmag.com/uploadedImages/Autonomous%20Robot.jpg
Embodiment (Distributed Intelligence)

- Brain (Controller)
- Body (Morphology) (Sensor, Actuator)
- Material Properties
- Environments
<table>
<thead>
<tr>
<th>Bio-inspiration</th>
<th>Design goals</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular replication</td>
<td>Self-assembly, self-replication, self-reconfiguration</td>
<td>Griffith et al. (2005); Miyashita et al. (2007); Murata and Kurokawa (2007); Ostergaard et al. (2005); Shen et al., (2006); Yim et al. (2007); Zykov et al. (2005); Zykov et al. (2007)</td>
</tr>
<tr>
<td>Slime molds</td>
<td>Locomotion</td>
<td>Ishiguro et al. (2006); Yokoi et al. (1998)</td>
</tr>
<tr>
<td>Ants as individuals</td>
<td>Navigation, homing</td>
<td>Lambrinos et al. (2000)</td>
</tr>
<tr>
<td>Ants as social insects</td>
<td>Swarm behavior, communication</td>
<td>Tuci et al. (2006); Gross et al. (2006); Floreano et al. (2007)</td>
</tr>
<tr>
<td>Bees as individuals</td>
<td>Navigation</td>
<td>Iida (2003); Srinivasan et al. (2004); Vardy and Moller (2005)</td>
</tr>
<tr>
<td>Bees as social insects</td>
<td>Swarm behavior, communication</td>
<td>Floreano et al. (2007)</td>
</tr>
<tr>
<td>Cricket</td>
<td>Phonotaxis</td>
<td>Reeve and Webb (2006); Reeve et al. (2005)</td>
</tr>
</tbody>
</table>
Slime Molds

http://renovatingtherustbelt.files.wordpress.com/2009/06/slimemold.jpg
<table>
<thead>
<tr>
<th>Animal</th>
<th>Locomotive Ability</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cockroach</td>
<td>Locomotion, mechanical feedback, self-stabilization</td>
<td>Cham et al. (2004); Koditschek et al. (2004); Quinn et al. (2003); Spagna et al. (2007)</td>
</tr>
<tr>
<td>Stick insect</td>
<td>Locomotion, neural control</td>
<td>Cruse et al. (1995); Cruse et al. (2002); Cruse et al. (2007)</td>
</tr>
<tr>
<td>Water strider</td>
<td>Locomotion, exploiting material properties</td>
<td>Song and Sitti (2007)</td>
</tr>
<tr>
<td>Moth</td>
<td>Chemotaxis, odor recognition</td>
<td>Bermudez i Badia et al. (2007); Lino and Anibal (2006)</td>
</tr>
<tr>
<td>Hummingbird</td>
<td>Flight, exploitation of materials, under-actuated systems</td>
<td>Madangopal et al. (2005)</td>
</tr>
<tr>
<td>Fly</td>
<td>Flight, exploitation of materials, under-actuated systems</td>
<td>Dickinson et al. (2000); Deng et al. (2006); Raiser and Dickinson (2003); Wood et al. (2007); Wood (2007)</td>
</tr>
</tbody>
</table>
Stick Insect

http://naturescrusaders.wordpress.com/2008/10/19/worlds-longest-stick-bug-from-borneo/
Water Strider

http://www.biosurvey.ou.edu/okwild/misc/images/waterstrider.jpg
<table>
<thead>
<tr>
<th>Fly</th>
<th>Sensor morphology adaptation</th>
<th>Lichtensteiger and Pfeifer (2002)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butterfly</td>
<td>Flight, exploitation of materials</td>
<td>Tanaka et al. (2005; 2006)</td>
</tr>
<tr>
<td>Scorpion</td>
<td>Locomotion</td>
<td>Klaasen et al. (2002)</td>
</tr>
<tr>
<td>Lobster</td>
<td>Plume following, underwater locomotion</td>
<td>Ayers and Witting (2007)</td>
</tr>
<tr>
<td>Octopus</td>
<td>Exploitation of materials</td>
<td>Jones and Walker (2006); Walker et al. (2006)</td>
</tr>
<tr>
<td>Snake</td>
<td>Locomotion</td>
<td>Hirose and Fukushima (2004); Hirose and Mori (2004); Sfakiotakis and Tsakiris (2007)</td>
</tr>
<tr>
<td>Fish</td>
<td>Underwater locomotion, materials</td>
<td>Pfeifer et al. (2006); Ziegler et al. (2006); Barrett et al. (1999); Triantafyllou and Triantafyllou (1995)</td>
</tr>
<tr>
<td>Animal</td>
<td>Movement Style</td>
<td>Notes</td>
</tr>
<tr>
<td>---------</td>
<td>----------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Manta-ray</td>
<td>Exploitation of materials, underwater locomotion</td>
<td>AQUA-RAY</td>
</tr>
<tr>
<td>Frog</td>
<td>Jumping, distributed control</td>
<td>Niyama et al. (2007)</td>
</tr>
<tr>
<td>Basilisk lizard</td>
<td>Running on water</td>
<td>Floyd et al. (2006)</td>
</tr>
<tr>
<td>Salamander</td>
<td>Transition between swimming and walking, neural modeling (CPGs)</td>
<td>Ijspeert et al. (2007)</td>
</tr>
<tr>
<td>Gecko</td>
<td>Climbing</td>
<td>Murphy and Sitti (2007)</td>
</tr>
<tr>
<td>Mouse</td>
<td>Neural modeling, morphology of whisker systems, multimodal integration</td>
<td>Fend et al. (2006); Kim and Moller (2007); Mitchinson et al. (2006); Solomon and Hartmann (2006)</td>
</tr>
<tr>
<td>Bat</td>
<td>Role of morphology in sound localization</td>
<td>Carmena and Hallam (2004)</td>
</tr>
<tr>
<td>Dog</td>
<td>Dynamics of rapid locomotion, self-</td>
<td>Aschenbeck et al. (2006); Kimura et al. (2007); Pfeifer et al. (2006)</td>
</tr>
</tbody>
</table>
Manta-Ray

http://consejo.bz/andros/fishphotos.html
Basilisk Lizards

http://www.flickr.com/photos/silbermanlaw/93409012/
<table>
<thead>
<tr>
<th>Animal</th>
<th>Behavior/Learning Aspect</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog</td>
<td>Entertainment, large behavioral diversity, learning</td>
<td>Fujita (2007)</td>
</tr>
<tr>
<td>Monkey</td>
<td>Brachiation, learning body dynamics</td>
<td>Fukuda et al. (2004)</td>
</tr>
<tr>
<td>Gorilla</td>
<td>Locomotion, compliant structures</td>
<td>Davis et al. (2006)</td>
</tr>
<tr>
<td>Human infants</td>
<td>Studying human development, push towards compact, integrated</td>
<td>Asada et al. (2001); Kuniyoshi et al. (2004); Lungarella and Berthouze (2002); Lungarella et al. (2003); Weng et al. (2000); Oudeyer et al. (2007); Tsagarakis et al. (2007); RobotCub; Synergistic Intelligence</td>
</tr>
<tr>
<td>Humans</td>
<td>Understanding human cognition, neural modeling</td>
<td>Cheng et al. (2007); Reeke et al. (1990)</td>
</tr>
<tr>
<td>Humans</td>
<td>Understanding human locomotion, manipulation</td>
<td>Collins et al. (2005); Geng et al. (2006); Holland and Knight (2007); Hosoda et al. (2006); Kemp et al. (2007); Scarfe and Lindsay (2006); Zollo et al. (2005);</td>
</tr>
<tr>
<td>Humans</td>
<td>Social interaction, development</td>
<td>Adams et al. (2000); Dautenhahn (2007); Demiris and Meltzoff (in press); Holland and Knight (2006); Kuniyoshi et al. (2004); Schaal et al. (2003); Tapus et al. (2007);</td>
</tr>
</tbody>
</table>
Intelligence by mechanics

Reinhard Blickhan, Andre Seyfarth, Hartmut Geyer, Sten Grimmer, Heiko Wagner and Michael Günther

Phil. Trans. R. Soc. A 2007 365, 199-220
doi: 10.1098/rsta.2006.1911
Mapping Information Flow in Sensorimotor Networks

Max Lungarella\(^1\), Olaf Sporns\(^2\)

1 Department of Mechano-Informatics, The University of Tokyo, Tokyo, Japan, 2 Department of Psychological and Brain Sciences, Indiana University, Bloomington, Indiana, United States of America
Can robots make good models of biological behaviour?

Barbara Webb
Department of Psychology, Centre for Computational and Cognitive Neuroscience, University of Stirling, Stirling FK9 4LA, Scotland, United Kingdom
b.h.webb@stir.ac.uk www.stir.ac.uk/psychology/Staff/bhw1/