Bioinsp. Biomim. **2** (2007) doi:10.1088/1748-3182/2/4/E01

EDITORIAL

Perspectives on biologically inspired design: introduction to the collected contributions

Guest Editors

Jeannette Yen and Marc Weissburg
School of Biology and Center for Biologically Inspired Design, 310 Ferst Dr., Georgia Institute of Technology, Atlanta, GA 30332-0230, USA

E-mail: jeannette.yen@biology.gatech.edu, marc.weissburg@biology.gatech.edu

Biologically inspired design (BID) or biomimicry consists of using biological principles to inform engineering designs and applications. As both a method and goal, BID therefore cuts across many disciplines that currently are organized around functional criteria (e.g. mechanical engineering) or levels of inquiry (e.g. cell biology). Two challenges arise from this disjunction: (1) Recognizing the fields, problems and applications for which BID has or can have an impact; (2) Understanding the basic steps required for a successful and deep fusion of biological and engineering knowledge. The need to develop a clearer picture of the breadth and depth of biologically inspired design was the basic impetus behind the *2006 International Conference in Biologically inspired Design in Science and Engineering* held at Georgia Tech. This conference is one of a number of recent efforts, particularly in the European community, that are drawing attention to the depth and breadth of biologically inspired design as practiced by a vigorous community of scientists and engineers.

The works presented in this special issue comprise some of the contributions of our 2006 conference, and cover a range of topics, areas and research approaches. Our goal is to enable a more global understanding of the impact of BID on current research and the identification of important steps (and constraints) in the on-going dialog between biologists and engineers. We are concerned with transference of biological principles to engineering designs and applications, but also with the role of engineering approaches in contributing to insights regarding fundamental biological questions. Each work outlines how biology–engineering connections are established and promoted within the context of a particular problem or field, through a combination of focal research descriptions, review and synthesis. Authors were specifically challenged with the task of discussing not only the tangible results for engineering or biological science, but also how and why specific biological systems or processes were chosen as representatives of potentially important engineering design features. In this way, we hope to illuminate what BID can do, but also to lend insights into how this framework may be successfully employed in the future.

Biologically inspired design is typically thought of as being problem based, that is, motivated by the desire to generate an improved or different solution to a particular technical challenge. Certainly, the works presented here provide many examples of problem driven approaches in areas of materials, sensing, locomotion/biomechanics and system organization. The inversion of this approach is to take biological 'solutions' as a starting point and seek out particular technical challenges for which the system is appropriate. The evidence from the symposia proceedings suggests that solution-based approaches are much less widely employed. It may simply be that scientists with expertise in biological systems are not sufficiently cognizant of potential applications. Consequently, it seems wise to ensure that intellectual exchange between biology and engineering is bidirectional; we may be missing considerable opportunities by inadequate support of both perspectives. Interestingly, solution-based approaches may encourage the application of biological principles in ways that would not be immediately obvious when viewed from a problem-based perspective. By example, certain traditional ways of doing things may not be considered as appropriate ‘problems’ without exposure to alternatives found in biological systems. It seems like the discovery of self-cleaning surfaces discussed by Solga *et al* has (along with societal pressures of water conservation) helped us to reassess the extent to which water usage is an inevitable requirement for cleaning. It also seems that when the biological systems comprise the starting point, the multi-functionality of biological systems encourages extension of biological principles to unanticipated domains. Solga *et al* also discuss how the range of problems for which ‘self-cleaning’ surfaces may represent effective solutions is not solely confined to removal of surface contaminants, but now includes prevention of colonization by biological agents and strategies to control water retention. In fact, the biological function of self-cleaning surfaces often addresses all of these problems. Thus, these mechanisms are now being applied to a larger range of areas than might be expected from a problem-based approach focused on removal of surface particulates. The benefits of the solution-based perspective are present in a number of contributions in this issue, but are especially apparent in the works of Solga *et al*, Nakrani and Tovey, Gorb *et al* and Gopal and Hartmann.

Associated with the problem-based versus solution-based dichotomy is the role of BID in the fields of engineering versus biology. The search for more efficient and innovative solutions clearly has driven much work in BID—the engineering application often is the primary motivation. However, it is becoming increasingly obvious that our understanding of some biological systems can be increased substantially by reproducing relevant biological properties in hardware or realistic simulation environments. Gopal and Hartmann discuss the idea of a sensor-bot, a reduced mechanical representation of a particular sensory system that combines both an artificial sensor and processing schema. This is a powerful approach when manipulating or intervening in a biological system is difficult or impossible. Liu points to similar advantages of engineered flow sensors to lend insight into their biological equivalent. Grasso and Setlur come to a number of interesting conclusions regarding important aspects of biological function via their physically realistic simulation environment. These devices and techniques allow tests of particular hypotheses about sensory acquisition, coding or neuromuscular coordination that cannot be done in living systems, given our inability to alter sensors or their configurations without detrimental side effects, or to legislate processing algorithms used by neural systems. The dictum that the act of building a complex system enables greater understanding is neither new nor confined to a particular field. For instance, the emerging articulation of synthetic biology embodies a similar belief that to create and to understand are intimately associated. Biologists take note—teaming with engineers may well provide you with an experimentally tractable system in which to formulate or test hypotheses, or generate predictions that can then be examined in the messier biological arena.

A clear message of our contributors is that translating biological principles into human devices or processes requires considerable technical proficiency. However, these collected works also argue that pure technical achievements are not the sole arbiter of success, and in fact may not always be the most important factor. A reasonable perspective is that the success of BID depends most critically on establishing the appropriate analogy between the problem to be solved and potential biological model systems. The strength of this analogy will in large measure determine how appropriate the resulting principles are when extracted from biology, and this step deserves at least as much analysis as the subsequent attempts to understand and implement principle. Clearly, some analogies are easier than others to build; it is relatively straightforward to accept that contact adhesion of manufactured surfaces is analogous to the ability of insects to walk on walls as argued by Gorb *et al*, perhaps since the obvious physical nature of the problem allows easy definition of parallelism between engineered and biological contexts. Other analogies are less clear and may involve considerable thought to identify the constraints in the human-centered problem that lead to the most accurate identification of biological solution. Such constraint or trait mapping is the essence of successful BID. The contribution by Liu, for instance, nicely articulates how and why specific biological flow sensors, hair cells, exemplify a series of desirable characteristics for particular sensing operations. On an even more abstract level, Nakrani and Tovey describe in careful and precise detail how they and their colleagues came to appreciate the deep analogy between honey bee foraging decisions and algorithms for internet server applications. This last case is also an archetypal example of the difference between using biological principles and superficial copying of biological systems or processes. Nakrani and Tovey extracted the basic decision rules (the biological principles) and applied them to a novel context. The resulting algorithm for internet hosting is unconnected to many of the original biological features, and hence is not especially mimetic although it clearly is inspired.

Although BID can produce innovative approaches to particular problems, a reasonable counterpoint is that the physical principles behind biologically based solutions are well known. What then, is the real contribution of BID to the design process? A second thread that runs through the collected work is that BID is a useful exercise because a particular biological solution often is employed in a large and diverse range of organisms. Excellent examples are provided in the works of Gorb *et al* and Müller and Kuc. As these authors suggest, the ability to examine the implementation of particular principles across many organisms aids in establishing both the generality and robustness of a particular biological 'solution'. Despite the fact that novel physical mechanisms may not be necessary, embedding even well-known mechanisms in a complex engineered system may be difficult to achieve without underlying observations that suggest the critical variables or features and their inter-relationships. Gorb and colleagues, for instance, articulate well a series of design 'rules' based on an analysis of properties shared across many organisms. A second advantage of the opportunity for comparison is that biological systems often are fine-tuned to solve a specific problem within the more general problem space. Bats use echolocation to detect objects, but each bat species 'looks' for specific objects in specific environments that vary from group to group. Müller and Kuc suggest that comparing different species may therefore allow us to examine particular combinations of features that allow for a given task, such that engineered systems with similar constraints may be constructed similarly. Having a pre-existing guide to fine-tuning such complex systems may be a considerable advantage given the intellectual and technical challenges in optimizing complex designs.

The interdisciplinary nature of BID presents complications that counterbalance its considerable potential. Even a cursory reading of the contributions assembled here makes plain the necessity for a fairly high level of biological expertise to identify appropriate biological systems and perhaps to perform essential experiments that may help establish how the system functions. The difficulty of choosing the appropriate biological models is heightened further since engineers, physical scientists and biologists often have different ways of describing even analogous functions. Anecdotal evidence gleaned from questioning many of our colleagues suggests that these barriers are surmounted more often when there is a pre-disposition for crossing the biology–engineering boundary; many instances of highly successful BID applications seem to have arisen due to an intrinsic fascination with biology that serves as a catalyst for the designer to look for inspiration in the natural world. Unfortunately, we have few examples of training programs that can promote exchange between biology and engineering and inspire designers to search the biological domain for potential solutions. Thus, we include the contribution of Bruck and colleagues, which may help others interested in developing methods fostering BID in particular, and interdisciplinary work in general. In the context of robotics, they describe a number of ways to bridge the gap between biological and engineering subject knowledge and reinforce the value of BID as a tool for innovative design. Student responses clearly indicate they were excited and inspired by considering biology as a source of design ideas and will seek to apply this perspective in the future. Our own experiences reinforce the trends discussed by Bruck *et al*, but suggest a further benefit to BID: engineers exposed to how biological systems solve problems often feel they have become better designers regardless of whether their final product incorporates biological principles. Many engineering students in our engineering senior design classes report that thinking about BID has led them to seek more widely for design solutions, even when they end up pursuing non-BID approaches. A challenge for future training programs is to incorporate a larger cross section of engineering and biological perspectives. As pointed out by Liu, and Grasso and Setlur (and others), important features of sensory or locomotory systems may be difficult to implement without corresponding advances in materials. Synergism is clearly required at the earliest training levels.

We hope that like these students, the scientists and engineers reading these contributions will be inspired and excited to take the challenge of further integrating deep biological principles with engineering. Progress in fundamental biology will require this fusion as we run up against the limits of reductionist approaches. Moreover, innovative engineering designs and processes will become increasingly important to minimize environmental harm and resource depletion, and we ignore at our peril the accumulated potential wisdom embedded in biological entities and processes. In closing, we wonder if BID will have significant effects beyond increasing our capacity for innovative life-friendly technology and greater biological understanding; can BID help redress the persistent antipathy between the human-built and natural worlds? Since we cannot learn from that which is destroyed, BID provides a tangible, practical and powerful argument for preserving our rapidly diminishing environment. In complement, exposing individuals to the remarkable achievements of life may provide the emotional connection that is the nascent spark of an environmental ethic. The material and immaterial potential benefits of biologically inspired design make this topic worthy of great consideration.

Acknowledgments

Our gratitude to Georgia Tech's Office of the Provost, the School of Industrial and Systems Engineering, and the National Science Foundation's Division of Manufacturing Innovation for providing funds for this conference. We thank our many energetic and insightful colleagues who attending this conference for their enthusiastic support. Special thanks to the individuals at the Biomimicry Guild for their inspiration, the members of the Center for Biologically Inspired Design at Georgia Tech for supporting the continuing conversation between biologists and engineers, and A Goel, M Helms and S Vattam for their perspectives on pedagogy.