Guest Editorial: Biology-Inspired Science and Technology for Autonomous Underwater Vehicles

THIS Special Issue is a contribution toward technologies for autonomy. The focus is on low-level autonomy, such as the adaptive response of autonomous vehicles, and not on any high-level control, such as missions lasting over days. The goal here is to thread certain apparently disparate science and technology disciplines together to provide the necessary foundation. In particular, we report the state of the art of the science and technology of maneuvering of aquatic animals and related disciplines with the purpose of implementation in autonomous underwater vehicles (AUV) to endow them with fish-like functional and operational abilities. It is hoped that this issue would stimulate future interdisciplinary research transitioning the sciences to technologies of Navy value.

This issue contains 24 papers in the Special Section. Fifteen of them are review papers commissioned by the Office of Naval Research (ONR) and nine are contributed papers. All of them, except one of the commissioned reviews, have been presented at the Biorobotics Workshop, held jointly with UUST03, the 13th International Symposium on Unmanned Untethered Submersible Technology, at Durham, NH, from August 24 to 27, 2003 (http://www.ausi.org). The first set of papers is divided into these three related groups: hydrodynamics (containing seven papers, six of which are reviews); control (all five are reviews); and actuators (containing seven papers, four of which are reviews) and more specifically in the disciplines unsteady hydrodynamics, neuroscience-based control, and artificial muscles. Next follow papers in a group called system development. Relatively speaking, the discipline of unsteady hydrodynamics/aerodynamics is the most developed; neuroscience-based control of swimming and flying animals is the least developed and artificial muscles, such as electro-active polymers, are by far currently the most amenable to the exploration of actuator product design. It is hoped that bringing these disciplines under one framework would foster their integration into products for AUVs. While the individual papers deal with maneuvering, the underlying thread that binds them is vehicle autonomy. The system integration of the disciplines is meant to achieve this.

I. BACKGROUND

From the point of view of basic and applied research, the broad rationale for biological inspiration in engineering may be viewed as shown schematically in a layered model in Fig. 1. Physics deals with fundamental forces, uncovers the laws of nature, and is the core of science. All other layers deal with application in one form or another. The first adjacent layer is chemistry, which can be described as applied molecular physics. The next outer layer is biology, which is nature's application of physics and chemistry into self-contained autonomous systems. We assign the next outer layer to engineering, which is man-made application of physics and chemistry. The disciplines are relatively treated as more basic as we approach the core and are more applied as we move to outer layers. Biology and engineering then both are basically design; the degrees of freedom, number of actuators, and sensors, redundancy, and autonomy generally decline in engineering systems as compared to biological systems. Because they are both designs and evolution leads to optimization, it is no wonder that in some instances there is convergence in their scaling laws and a gap in others, which, however, is closing rapidly with progress in the sciences and technologies. For example, in underwater cruising, there is convergence in the scaling law of shaft horse power to displacement between red muscles of high-performance species of fish and all submarines that extend over eight decades [1]. On the other hand, there still exists a gap in the turning abilities of fish and tactical scale underwater vehicles, which, however, is closing over the last five decades [2]. More specifically, in the present context, the rationale is as follows. Swimming and flying engineering platforms are based on steady-state hydrodynamics and have reached a high level of perfection. While they have a maximum coefficient of lift of 1–1.5 and stall at $O(15^\circ)$, heaving and pitching foils have a maximum lift coefficient of 4–5 and stall is delayed beyond even 60°. Engineers have been aware of these benefits of unsteady mechanisms, but cost and reliability issues of high degree of freedom systems built with conventional materials and control have deterred their implementation. Biological systems, on the other hand, can have higher degrees of freedom, are reliable over many cycles of operation, and have striking vehicle performance, at least in measures of length-to-speed ratio, power consumption for maneuvering, and turning ability, compared to engineering underwater platforms. Ellington *et al.* [3], Ellington [4], and Dickinson *et al.* [5] have shown that flying insects resort to heaving and pitching wings to support their mass in air, which otherwise could not have been possible with steady-state aerodynamics. In other words, nature has indeed built self-contained autonomous systems in which unsteady lifting mechanisms are feasible. However, natural muscles and neuroscience-based control are integrated with unsteady actuators in these natural systems. Hence, the present issue also seeks to bridge the aforementioned three disciplines.

The recent focus on biology-based engineering can be traced to the vision of reverse engineering due to Dr. F. E. Saalfeld, Dr. W. S. Vaughan, and several Program Officers at ONR and

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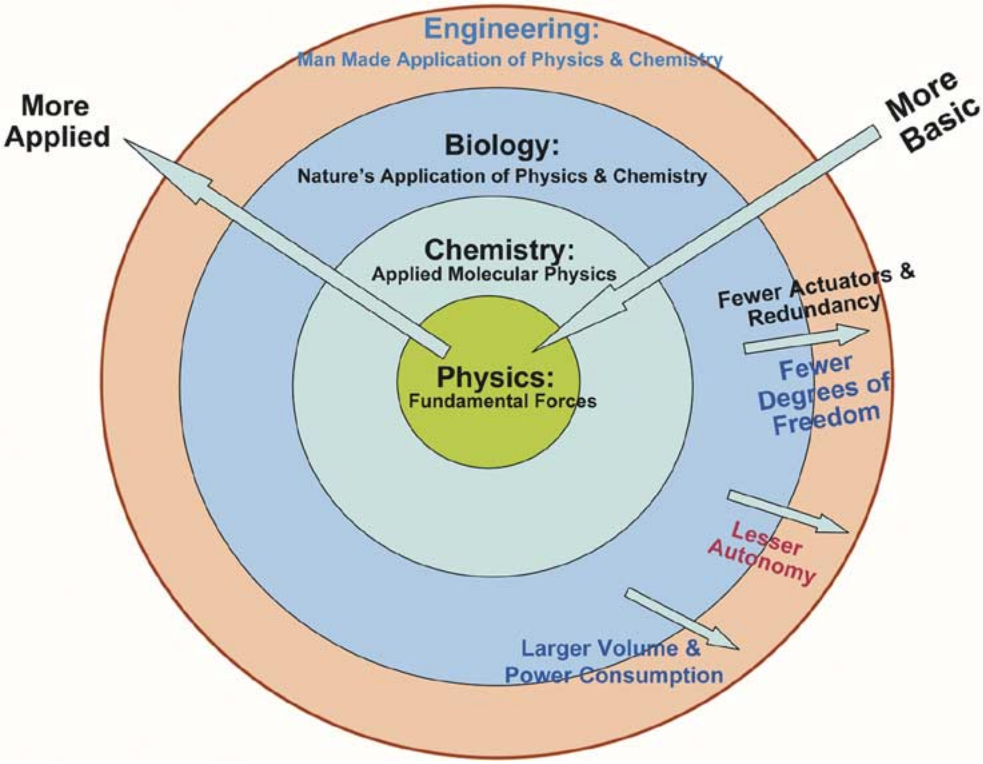

Fig. 1. Schematic of the close relationship between biology and engineering.

the Defense Advanced Research Projects Agency (DARPA), notably Dr. T. McMullen, Dr. H. Hawkins, Dr. T. McKenna, Dr. R. Gisiner, Dr. K. Ward, Dr. H. Bright, and Dr. A. Rudolf. Saalfeld has described swimming animals as a learning model of platform autonomy. The present focus on maneuvering and on the fish pectoral fin as a control surface for achieving that is a departure from the earlier focus of biorobotics on propulsion. Navy propulsors reached high efficiency during the cold war, when the emphasis had been on cruise and speed. However, after the cold war, research at Naval Undersea Warfare Center (NUWC) shifted the focus of biorobotics to maneuvering from propulsion due to increased interest in littoral regions. The gap in maneuverability between fish and small underwater vehicles was quantified and was found to be large. The gap was attributed to hydrodynamic mechanisms and control technology. The present effort to bring the three disciplines together owes its origin to this NUWC result.

In the first group of papers, there are seven papers on hydrodynamics, the first six being commissioned reviews in a team framework of biology and their transition to engineering. The seventh describes a diagnostic sensor suited to the integration of unsteady hydrodynamics and control. In the second group, there are five commissioned reviews on control in a whole-body context; they are written in a complementary team framework of biology and engineering. Third, there are seven papers on actuators, the first four of which are commissioned reviews spanning mechanisms to engineering design, again in a team framework of biology and engineering. Fourth, there are five contributed papers that deal with biology-inspired integrated systems for AUVs.

II. HYDRODYNAMICS

In the first paper, which is a review, Webb scopes the subject of maneuverability in an elementary mechanics framework drawing primarily from fish swimming. Maneuverability is seen as a complicated integration of actuators and control to carry out a vast array of whole-body gymnastics in the pursuit of a mission archetypical of the species or the AUV. It is sobering to start with a paper that is urging caution in the degree of mimicry that one should expect to be valid and, instead, commonality in the mission of the model fish and AUV should be the key criterion. This echoes this issue's emphasis on the extraction of science principles in maneuvering in the world of biology and applies them to engineering, rather than mimic forms in biology.

In the second paper, which is also a review, Lauder and Drucker review experimental research on fish maneuvering. This paper is at the fault line between evolutionary fish biology and platform engineering in the sense that while engineers seek minimalist mechanisms for implementation, the former explores diversity. Fish swimming emerges as an integrated actuator-control architecture in which vectored arrays of ring vortices are produced by means of phased motion of usually multiple flexible fins. Although much has been written on fish motion, the mechanisms of force production by fins are largely unknown. Thus, what science will transition to engineering remains an open question. But with new electro-active materials being developed as reviewed in this issue, the integration of actuators and control into subsystems could prove fruitful.

The next paper is a review by Walker. This is also on fish fins that act as control surfaces for maneuvering. This paper has some elementary mechanics modeling and a summary of fish fins optimized for specific kinds of maneuvering. The discussion of the role of spanwise twisting is a pace setting example of issues that need to be addressed to transition the sciences to engineering. Heave, pitch, twist, and flexibility of fins are design implementations of yet unknown mechanisms. Therefore, we now need quantitative information of dynamic forces on the fins (via mechanical models), such as limiting streamline patterns, migration of stagnation lines, and surface pressure distribution history to understand the mechanisms such as dynamic stall, rotational effects, or wake capture as in insect flight.

The fourth paper switches to engineering and is by Triantafyllou *et al.* This also is a review. It summarizes what we have learned via controlled laboratory experiments with mechanical models of fins, which make the results less ambiguous. This paper reveals a great understanding of the differences in mechanism that are in play, at least to the extent we know, in insect flight and fish swimming. In flying, generation of lift is paramount and dynamic stall is a central mechanism to achieve that. On the other hand, drag and thrust are more important in swimming and chord-wise flexibility is a means of achieving propulsive efficiency.

We pin our hope of resolving the mechanisms in the most unambiguous manner on computational fluid dynamics. In the next paper, Mittal reviews the state of the starting line. The issues are accuracy at high Reynolds numbers and the treatment of flexible fin surfaces. Very little computational progress has been made with three-dimensional (3-D) fish fins attached to a fish body or transplanted to a rigid cylinder.

The next review, which is by Fish, shifts to the control surfaces in nonfish species/animals, particularly the flippers of dolphins, penguins, sea lions, and whales. The size of these animals is of the order of AUVs. The foil sections are not particularly different from what are known to engineers, which probably represents the optimization due to steady-state hydrodynamics. But swimming animals use the flippers for unsteady mechanisms. In other words, the key features of flippers lie not even in unsteady hydrodynamics, but in unsteady structure-hydrodynamics interactions. Future investments should be in such unsteady fluid-structure research. We need to determine elastic properties of such live active flippers, their resonant properties, and impact on efficiency and power. Added mass effects might turn out to be the largest practical difference between the unsteady mechanisms practiced by swimming and flying animals.

In the next paper, Mangalam presents a multielement hot-film shear sensor that can be used as an indicator of real-time unsteady loads on actuators and for the diagnostics of critical point flow features on the surface that are the signatures of the force production mechanism. The former ability could be used to balance rotors if their individual foils produce large unsteady loads.

III. CONTROL

The papers in the control group address the question of how to control the many actuators on a body based on biological principles. Vertebrates coordinate their physical movement from a part of the brain called olivo-cerebellum. In the first paper, Llinas *et al.* report the progress with control via the mapping of the network properties of the olivo-cerebellar system on microchips. The underlying nonlinear dynamics of coupled oscillator analog systems appear to have a profound potential in being faster than digital chips and even achieve the tantalizing appeal of closing the gap with quantum limits of time resolution.

Multicellular organisms from fish to humans perform complex motions and the nervous system has evolved to make that possible. In the next paper, Mussa-Ivaldi and Solla present a perspective of neural control of motions. Their definition of adaptation as the ability to carry out previously learned motor skills into new mechanical contexts is intriguing from the context of AUVs. Unlike those in animals, the actuators in an AUV would not change with maturity. So, the question is: Could we make AUVs adaptable by the use of Llinas' brain neuroscience-based controller? As there are denominations of bills to arrive at any desired cash amount, animals have sets of elementary motor behaviors that they use to produce any necessary complex motion. Instead of solving differential equations to carry out a control task, perhaps the AUV motion could be produced by summing its own elementary motor behaviors.

AUVs are platforms for sensors tasked to carry out a mission. MacIver *et al.* are proposing that sensors, their clustering over the body, the propulsion system, and the main body should be codesigned. This is based on the correlation between sensors and trajectories in black ghost knifefish, which is weakly electric and hunts in darkness in the muddy waters of Amazon.

In the next paper, Colgate and Lynch have reviewed the engineering control issues of swimming machines that mimic fish. Hydrodynamics and control have been integrated.

Unlike bird or insect wings that have evolved for a low-density medium-like air, fish pectoral fins undergo a great deal of twisting along chord and span. Westneat, Thorsen, Walker, and Hale discuss the anatomy and the mechanics of fin.

IV. ARTIFICIAL MUSCLE ACTUATORS

Active control requires consideration of cost and reliability. Animal muscles have reached a high level of perfection in these regards. The anatomy and mechanisms of skeletal muscles of vertebrates have been reviewed by King *et al.* They summarize design principles that could guide the development of integrated engineering actuator-control systems.

Skeletal muscles have high molecular weight and are flexible. However, they have low work density and tend to have no catch state (it needs energy to maintain force without moving). Engineering materials tend to be of low molecular weight and are rigid, while they have a wide variety of useful properties. Now, consider polymer, which is a novel engineering material but not yet widely used as actuator materials. Polymers, in contrast to conventional engineering actuator materials, have the promise of being flexible and of high molecular weight and yet have an array of desired engineering properties. The development of these materials is reviewed in the next three papers. In the first paper of this polymer actuator subgroup, Yu and Swager briefly review polymer design at the molecular level. The goal is to fabricate polymers that produce large deflections with fast response. The focus is on the design of a molecular building block of actuation that acts like a hinge. The work is at the one-dimensional level and transition of the science to the bulk material stage needs to be addressed. In the second paper, Madden, Madden *et al.* discuss mechanism based modeling of the behavior of electro-active polymer materials. This would help quality control of manufacturing and prediction of behavior. In the third paper, Madden, Vandsteeg *et al.* present comprehensive and practical reviews of a range of actuator materials from shape memory alloys (SMA) to carbon nanotube polymers that are at various stages of maturity—from developed to emerging. They also present two design case studies on small and large AUVs to determine what materials meet their hydrodynamic requirements. Polymers, elastomers, and SMAs have the desired properties, but practical issues remain. We also ask whether some of the appealing emerging materials would retain their arrays of attractive properties when manufactured in bulk quantities.

In the remaining part of this group, there are three contributed papers regarding the application of artificial muscles. In the first, Paquette and Kim present a propulsor design case study using ionic polymer–metal composites. Practical fabrication issues are discussed. In the next paper, Madden *et al.* present the application of polypyrrole to propulsor foils of small AUVs. They demonstrate that target force and deflection can be achieved with a high work density by a combination of layers of polypyrrole and a mechanical amplifier of ratio 25. However, fabrication challenges remain. In the final paper of this group, Shinjo and Swain present a preliminary design exercise in the footsteps of the Massachusetts Institute of Technology (MIT) Robotuna. While Robotuna replicated the caudal fin hydrodynamics mechanism, this approach mimics the axial tendon and muscle configuration in fish, with shape memory alloy wires utilizing elastic energy to generate the caudal fin motion for propulsion. The design mimicry appears to alleviate the strain limitations of SMA.

V. System Development

In the final group, there are five contributed papers that integrate several disciplines in a vehicle context. The first two attempt to improve the performance of propulsors by implementing hydrodynamic mechanisms that are successful in flying and swimming animals. The first, by Usab, Hardin, and Bilanin, is a beautiful example of how to distill science from biolocomotion and implement only these principles on existing engineering products to facilitate customer transition. This is a faster route to transition to engineering from science than superficial biomimicry. Their ingenuous application of delayed stall, the most powerful of the three mechanisms of insect flight, leads to larger stall margins in compressors. We now wait for demonstration in water.

It is known that the oscillations of the caudal fin of a fish produce a jet in contrast to a wake, which is momentum deficient, that would be produced had there been no oscillations. Inspired by this, in the second paper, Opila *et al.* present an analysis and experiment where the trailing edge of an upstream stator foil is oscillated just enough to fill up its wake momentum deficit and reduce buffeting on the downstream rotor foil. The results are encouraging. We now need to know if the concept can be scaled up to higher Reynolds numbers.

One goal of Biorobotic AUVs would be to supplant dolphins from the task of mine detection. We assume that Biosonars on an AUV with precision maneuvering ability would fit the bill. The ONR–DARPA Biosonar program carried out runs to collect the onboard sonar and motion data of instrumented dolphins engaged for the task of mine detection. The work of Singh and Mittal is addressing the question whether rigid cylindrical AUVs attached with fish-like pectoral fins can match the reference motion of such dolphins. They integrate hydrodynamic characteristics obtained with computational techniques with theoretical control tools. Pitch bias is found to be a simple "knob" to control maneuvering. This is echoed in the paper by Licht *et al.* in this issue. Such simple consensus prescriptions for bulk engineering tasks such as maneuvering would facilitate transition of biology-inspired hydrodynamics mechanisms to platforms.

Next, Licht *et al.* present the design, predicted performance, and control features of a biology-inspired AUV fitted with several heaving and pitching foils. The vehicle is predicted to reach a cruise speed of 4 kn, but power consumption is not comparable to that in conventional AUVs. The maneuvering performance remains to be compared. Again, pitch bias angle is found to be a simple linear "knob" for controlling lift force produced by heaving and pitching foils. Their AUV could be useful as a research vehicle for systems and maneuvering studies.

Each swimming and flying species tends to have some general features and some typical features that sometimes could have counterintuitive characteristics. Many microorganizms and larval aquatic animals swim in helical trajectories. In the final paper, Long *et al.* present results of a robotic tadpole, which swims in such a manner toward the target and then "holds station" in that general area.

VI. Concluding Remarks

What are the benchmarks for transition of the sciences into technologies in the AUV context? The sciences need to be distilled and mechanisms extracted. In contrast to mimicry, in order to transition to engineering, inventions need to ingeniously implement those mechanisms, preferably in a passive manner and into an existing system to improve its performance. If a system is active, then cost (penalty) should be low and reliability should be high. Based on flying insects, the budget of mechanisms for lift production due to unsteady aerodynamics/hydrodynamics, is estimated as follows: dynamic stall is O (60%), rotational lift is O (30%), and wake capture is O (10%). Implementing the latter two is a challenge due to cost and reliability. Primarily, dynamic stall has a higher probability of transition to a Navy product. What new unsteady lifting mechanism can we expect from research on swimming animals? The flexibility of lifting surfaces could alter the budget of dynamic stall via the dynamics of stagnation lines. They could also provide clues to reduction of foil span for practicality. The added mass effect has not been quantified. Artificial muscles such as electro-active polymers now match the properties of natural muscles in a broad range of performance matrix. These properties need to be enhanced by factors of 10–100 to reach the levels of metals and become attractive to engineering as actuator materials and they need to come down in cost by similar orders of magnitudes. For neuroscience-based controllers to be attractive, they need to perform faster and better by a factor of 10 or higher than that based on current digital chips and relevant typical linear algorithms. Integration of the three disciplines, particularly those of artificial muscles and neuroscience-based algorithms and chips into subsystems, seem only limited by imagination. A platform by itself is of little value. The integration of Biorobotic AUVs, as conceptualized here, with sensors, communication systems, and networking intelligence, would truly lead to advanced autonomy.

The ONR has sponsored the research reported in many of the papers contained here. The numerous reviewers who remain anonymous have enthusiastically contributed. The present Special Issue is a result of this shared vision. It is hoped that this issue will help guide future investments and direction of research.

[1] P. R. Bandyopadhyay and M. Boller, "Convergence in underwater swimming between nature and engineering," presented at the Annu. Meeting Division of Fluid Dynamics,, Seattle, WA, Nov. 2004. American Physical Society, Paper KD.002.
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[3] C. P. Ellington, C. v. d Berg, A. P. Willmott, and A. L. R. Thomas, "Leading-edge vortices in insect flight," *Nature*, vol. 384, pp. 626–630, 1996.
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PROMODE R. BANDYOPADHYAY, *Guest Editor*
Naval Undersea Warfare Center
Newport, RI 02841-1708 USA
BandyopadhyayPR@Npt.NUWC.Navy.Mil

Promode R. Bandyopadhyay received the B.S. degree in mechanical engineering from the University of North Bengal, Darjeeling, India, the M.S. degree from the University of Calcutta, Calcutta, India, and the Ph.D. degree from the Indian Institute of Technology, Madras, India, and the University of Cambridge, Cambridge, U.K., in 1968, 1970, 1974, and 1978, respectively.

He was an Adjunct Faculty Member with Old Dominion University (ODU), Norfolk, VA, and the University of Rhode Island (URI), Kingston. This Special Issue was conceived while he was managing the Office of Naval Research (ONR) Biorobotics Program during 2001–2003. He is currently with the Naval Undersea Warfare Center, Newport, where he carries out research on technologies for biology-inspired autonomy and turbulence control. His work has led to the quantification of the gap in maneuverability between fish and tactical scale undersea vehicles. He also led the Naval Undersea Warfare Center–Russia–UK compliant coating research project. While at NASA Langley Research Center, Hampton, VA, earlier as an in-house contractor, he designed a stepped axisymmetric nose employing the convex curvature concept of viscous drag reduction, which has been found to have evolved in certain aquatic animals. There, he also experimentally described the regeneration mechanism of turbulent trailing vortex, which has since been confirmed by direct numerical simulation. His rough wall turbulent boundary layer data has been widely used for code validation. While at Cambridge, via a simple experiment, he, with M. R. Head, elucidated the inclined organized hairpin vortex structure of turbulent boundary layers and the thinning effect of increasing Reynolds number on them, which have been subsequently confirmed by numerous simulations and experiments. Four of his works are cited in 12 textbooks. He was the founding editor of the ASME volume on the Application of Microfabrication to Fluid Mechanics and has served as the Associate Editor of *AIAA Journal* and *ASME Journal of Fluids Engineering*.

Dr. Bandyopadhyay is a Fellow of the American Society of Mechanical Engineers (ASME) and Wolfson College, University of Cambridge. He has received the NASA Award for Technology Utilization and Application for a skin friction meter.