The Seventeenth International Symposium on Artificial Life and Robotics 2012 (AROB 17th '12),
B-Con Plaza, Beppu, Oita, Japan, January 19-21, 2012

Bioinspiration and Modern Actuators

Maki K Habib[1], Keigo Watanabe[2], and Fusaomi Nagata[3]

[1]The American University in Cairo, New Cairo, Egypt
[2]Okayama University, Okayama, Japan
[3]Tokyo University of Science, Yamaguchi, Japan

[1]maki@aucegypt.edu

Abstract: Biological systems in nature went through long evolution process that led to highly effective and efficient systems with excellent performance. Biomimetics is an interdisciplinary scientific research focuses on making nature as new sources of inspiration to study, analyze and design of creative and efficient engineering systems supported by innovative technologies. Smart materials are the foundation supporting the development of creative bioinpiration. Wide range of biologically inspired systems have been developed. However, engineering such biomimetic intelligent creatures were hampered by physical and technological constraints, and it is still a challenge. Actuators are essential elements within Mechatronical systems due to their important role in motion control systems and hence the development of modern actuators can be inspired from biological actuation systems in nature associated with different level of control. Making intelligent creatures that are actuated by biologically inspired modern actuators and artificial muscles would create new reality with great potentials. This paper provides the concept of Biomimetic as an interdisciplinary field, discusses the enabling technologies, and presents the development of biologically inspired actuators.

Keywords: Bioinspiration, Biomimetic, Intelligent creature, Modern actuators, and Artificial muscles.

I. INTRODUCTION

The evolution of nature led to the introduction of highly effective and power efficient biological systems in general and mechanisms in specific. Nature tested every field of science and engineering leading to inventions that work well, can adapt and last. Biological systems exhibit remarkable physical properties and have been a source of inspiration. Adopting mechanisms and capabilities from nature and the use of scientific approaches led to effective materials, structures, tools, mechanisms, processes, algorithms, methods, systems and many other benefits. Nature has always served as a model for mimicking and inspiration to humans in their efforts to improve their life. Humans throughout history have always sought to mimic the appearance, mobility, functionality, intelligent operation, and thinking process of biological creatures [1].

Maturing conventional technologies are associated with constraints and inadequate performance and this foster the demand for new solutions to maximize functionality while minimizing costs in energy and materials. The need to seek for new solutions is driving science to consider nature as biologically inspired model. The driving force behind attempting to merge biological principles and physics applications stems from the recognition that there are a number of areas where biological methods are more efficient, environmentally and ecologically friendly, and overall superior to current technology. Hence, understanding biological systems presents unique opportunities for wide range development of innovative ideas, paradigms, concepts and methods for engineering solutions, and helps to create new generations of smart materials, novel advanced structures, intelligent devices and technologies. Engineers are increasingly turning to biologists to understand and learn how living organisms function and solve problems. This leads to fuse the best solutions from nature with artificially engineered components to develop systems that are better in functions and efficiency than existing conventional approaches, and this science and technology became known as "Biomimetics" or the 'Mimicry of Nature'. Researchers diverge in precisely how they define biomimetics [2]. However, the use of inspiration instead of mimics is a more accurate description since mimicry is neither possible nor desirable.

Biomimetics can be defined as a new interdisciplinary scientific field featured by technology outcome (hardware and software), and it lies at the interface between biology, physics, chemistry, information, and engineering sciences [3]. Biomimetics focuses on making nature as a model of inspiration that would immensely help conscious abstraction of new principles and ideas, foster innovative design collections, find out new techniques and functionalities, seek new paradigms and methods, develop new materials, and design new streams of intelligent machines, robots, systems, devices, algorithms, etc. Biomimetics incorporates building novel materials at nature's scale and techniques drawn from naturally made substances, and resembles biological systems in structure and/or function as necessary. In the field of sensing and actuations, biomimetics devices can provide an efficient way of converting mechanical energy into electrical or chemical forms and vice versa. Scientists hope this blending may one day lead to stronger, cost- and energy-efficient, and intelligent products that are attractive ecologically.

Making creatures that look and behave like biological models, such as robots and toys that are greatly inspired by science fiction, have established perceptions and expectations that are far beyond the reach of current engineering capabilities, which are constrained by laws of physics and current state-of-the-art. The accelerating pace of the advancements in the field of biomimetics seems to make evident that the emergence of machines as our peers is imminent. Further advancement and the actual realization of these possibilities depends on a number of factors, including local acceptance of technological change, levels of technology and infrastructure investments, market drivers and limitations, and technology breakthroughs and advancements.

II. BIOLOGICALLY INSPIRED ACTUATION

Actuation presents constraints to novel designs of intelligent mechanisms. Different types of actuators have been developed and used. Three types of conventional actuation are considered as the core of motion and force power for all motion based systems: Hydraulic, Pneumatic, and Electromagnetic actuators. These three come from two main types of power conversion. The first two are considered fluid machines in that they use fluid to create mechanical motion whereas the electric motor converts electrical energy into mechanical energy. Electromagnetic actuators are considered as practical solution for some applications, but these actuators are not ideal in providing the necessary and comparatively high torque and their overall power density is typically low. In addition, most electromagnetic devices cannot supply sufficient energy in a single stroke. Hence various complex transmissions means such as gear boxes, pulleys, etc. are required. However, heavy and inefficient electromagnetic actuation and mechanisms remain the convention not only for robots but also for other motion devices in general. The challenges of energy inefficiency, flexibility, stability and maneuverability, robustness and other technical motivations have been many in getting robots to perform bio-inspired motion, such as that of human, animal, insect, etc (The properties of the muscles vary by species). Hence, there are demands to develop technologies that would drive robots with efficient, high power density actuation, stability and speed in a variety of natural environment to achieve lifelike motion performance. The most significant difficulty in achieving lifelike performance or appearance is the lack of actuator technology that can truly mimic natural muscles even at its most basic performance.

Natural muscles are essential to the mobility and manipulation capabilities of biological creatures. Skeletal muscle accounts for nearly half of the total mass of the average adult human and is unique in its ability to actively modify its mechanical properties within tens of milliseconds to allow human and animals to rapidly react to different environment needs. Muscle is a linear actuator technology whose properties are very well suited to provide intermittent displacements and variable stiffness in organisms ranging from micrometers to meters in length. In addition, muscle is a multifunctional and a 3D nanofabricated element with integrated circulation system (delivers energy (fuel) and removes heat and waste), good work density, act as energy absorber and repair mechanisms. The efficiency and plasticity that characterize muscles arise from the properties of biomolecular motors. Muscle cells serve to self-organize, maintain, repair, and control the mechanical actions of large arrays of biomolecular motors. Tendon tissue is an extension of the extracellular matrix muscle (ECM) and muscle tendon junctions at the ends of each muscle fiber. The mechanical structures that make up this transition from muscle to tendon are critical for the transduction of force, work, and power between muscle tissue and the external environment [4]. In order to achieve desirable bio-inspired motion, such as human, animal, insect, etc. like motions, actuators must be able to reproduce the important features of natural muscle such as adaptable stiffness, high energy, moderate stress and large strain, response speed, efficiency, controllability and high cycle life. Although tremendous technological progress has been made and some artificial actuator technologies are already matching or exceeding muscle in strain, stress, and specific power they cannot yet perform as well as their biological counterparts, whether in terms of stability, fatigue-life or speed [5]. Biomimetics is not limited in mimicking the appearance of natural organisms and surpass the general properties of natural muscles, rather to achieve natural superior behavior and performance. The hope is to develop intelligent robots and machines that are independent, flexible, light in weight, high level of autonomy with capability to learn and adjust their behavior within their dynamic environment. This highlights the need and the necessity to develop actuators that emulate and supersede the behavior and performance of natural muscles. The potential to make such actuators is increasingly becoming feasible with the emergence of new development and technologies.

Many new types of actuators and materials have been used or currently under development to provide the necessary motion and force input. Examples of these actuators are Shape Memory Alloys, Electro-Rheological Fluids, Magneto-Active Transducers, single Crystal Piezoelectric ceramics, Carbon nanotubes, Electrostatic, and Electroactive Polymers. Although natural muscle is not the best in many individual categories of performance, such as strain, actuation power/stress, density, efficiency, actuation speeds, etc, they are still superior in their behavioral performance. This leads to the observation that conventional technologies fail to achieve lifelike motion not because they cannot match or exceed natural muscle performance in any given performance measure, but rather they fall short because their overall performance is not yet comparable to that of natural muscle [6]. In addition, the comparison between the available technologies shows that the electrostatic actuators meet all the stated individual categories of performance requirements for an artificial muscle except in actuation stress. The same comparison shows that dielectric elastomers (DE) can also achieve good overall performance compared to that of natural muscles. Elastomers are sufficiently compliant that large strains are induced and there is efficient coupling between the electrical energy input and mechanical energy output. Electroactive polymers artificial muscles (EPAM), and dielectric elastomers, electro-elastromers are two terms used to indicate to electroactive polymers. Hence, it would be possible to view dielectric elastomer technology as a way to increase actuation stress in electrostatic actuators or as a muscle-like actuator technology in its own right. Research into natural muscle shows that muscle has a number of important passive properties, such as passive elasticity, damping, braking functions (actively absorbing mechanical energy beyond simple damping), and even integrated sensing [7, 8], which help organisms achieve remarkable dynamic performance in the presence of obstacles and unexpected perturbations. While probably not all these functions are needed simultaneously to achieve lifelike motion and/or performance in many cases, the biomimetic actuator designer must consider the range of natural muscle capabilities and how they relate to the capabilities of a given actuator technology. While dielectric elastomers are not an exact analogue of natural muscle, they capture many of the important general features of natural muscle such as stress, high fracture toughness, damage tolerance, inherent vibration damping, large actuation strains, and elasticity. Dielectric elastomers have been operated successfully between 250 ^{o}C, and at -100 ^{o}C for silicones and -10 ^{o}C and 90 ^{o}C for acrylic [9]. However, there are still some of the limitations associated with this technology such as, the need to convert line or battery voltages, which adds cost and consumes volume. Also, pre-stretching mechanisms currently add substantial mass and volume. In addition, the dielectric breakdown can limit actuator yield especially when imperfections exist within films [9].

Synthetic and tissue based technologies of smart materials, such as the category of electroactive polymers (EAP), which includes EPAM, and the electrostrictive polymers [10-12] which, change its dielectric constant as part of the actuation mechanism. These technologies are rapidly emerging as quantitatively functional equivalents to muscle tissue. Electrostrictive polymers have comparable performance to many types of EPAM, but they are typically stiffer and have lower strains. EPAM has demonstrated promise for a variety of applications since it represents a significant difference not only from the conventional electromagnetic actuators but also from other emerging technologies like piezoelectric crystals and shape memory alloys (SMA). Piezoelectric polymers, such as PVDF material have found some non-robotic applications, but for robots, it has relatively low power and energy density. More recently, other types of polymers have been investigated, such as electrochemically actuated conducting polymers and gels (sometimes referred as ionic polymers) that are actuated through the use of chemical changes driven by low voltage signal [10]. In spite of the attractive features of these polymers in terms of low voltage operation and good actuation pressure, they have limited performance in relation to robotic applications because of their relatively slow speeds and low efficiency. Nickel Titanium (NiTi or Nitinol) are the most extensively studied SMA and used as artificial muscles because of their relative nontoxicity, reasonable cost and an electrical resistivity [13, 14]. Martensitic transformations are at the heart of the shape memory effect. Shape memory alloys can exert very large forces per unit area, operate at very high strain rates and undergo relatively large deformations [13, 14]. One of the difficulties that limit the use of SMA as impede their use as muscle-like actuators is the difficulty of controlling the length of NiTi fibers as they undergo a phase transformation (usually run between fully contracted and fully extended but not between). In addition, NiTi actuators have a limited cycle life and their shape memory effect degrades significantly at very large strains.

The most significant advantage EPAM has over electromagnetic actuators is energy density, i.e., more energy created per unit mass of the actuator itself. EPAM demonstrated energy density of 3.4 [J/g] and this density is about 21 times that of single crystal piezoelectric. The energy density gains from EPAM will bring mobility and flexibility to robots and other intelligent machines. In addition, with regards to shape memory alloy and piezoelectric technology, EPAM has a significant direct displacement advantage. While shape memory alloy and piezoelectric technology might get a 1 per-cent direct displacement, EPAM actuators can reach 20-30 per cent levels over long life cycles. With respect to conventional electromagnetic motors, EPAM has a significant advantage in power density. EPAM will provide the same level of power as an EM motor device but with a much smaller and lower weight form factor, much like the human muscle [15]. Furthermore, one can have multi layer of EPAM to get additional displacement or stroke as well as getting higher exerted forces. These layers can be constructed in multiple planar configurations or in linear rolls. In addition, EPAM can be patterned to pinpoint actuation in multiple locations. The overall displacement is a function of the area of EPAM, and the force exerted is a function of the number of layers of EPAM. These layers can be constructed in multiple planar configurations. The electrode layer of the EPAM can be patterned to achieve specific envelopes of motion. Further work will undoubtedly improve the match of EPAM to natural muscle.

Most of the presented newly developed actuator technologies require electrical energy and will generally rely on batteries when used in autonomous systems such as autonomous mobile robots. Cost, energy density and cycle life of fuel cells will alleviate this issue in systems on ground and space. Submersible use is challenging as both fuel cells and chemical oxidation reactions require the harvesting of dissolved oxygen and of air bubbles. Though batteries can be used for autonomous robots, current battery technology store too little energy and deliver it at too low a rate for prolonged or intense activity. The most advanced battery can only store about one-thirtieth of the energy that is stored chemically in fuels such as methanol. To solve these problems, new muscle fibers have been developed just like real muscles [6]. They can power themselves instead of relying on external electrical power. Among the developed artificial muscles of this type is a nickel-titanium alloy coated with platinum, which causes the fuel, currently methanol (hydrogen or alcohol could work, too) to react with oxygen, producing heat. The metal shrinks; the muscle flexes. The artificial muscle can apply 100 times as much force as real muscle. The other artificial muscle, currently less powerful, is made of a sheet of carbon nanotubes, tiny but super strong cylindrical molecules of carbon. Carbon nanotubes are hollow cylinders that are typically 1.2 nm in diameter or larger. Their structure is that of a single rolled sheet of graphite that can have lengths on the

© ISAROB 2012

micrometer scale [16, 17]. The reaction of fuel and oxygen releases electrical charges that repel each other and cause the nanotube sheet to expand. In order to put such artificial muscles into robots will require solving other problems, like how to control the amount of fuel going to the muscles. In addition, the small to moderate strains characterizing current carbon nanotube actuators require some mechanical amplification, while the electromechanical coupling is poor and require energy recovery to achieve better efficiency. It is expected to overcome many of these issues and promise to provide better performance [17].

III. BIOMIMETICS: CHALLENGES AND INNOVATIONS

None of the available intelligent systems and mechanisms has yet reached the flexibility, adaptability and performance of biological systems, such as human, cheetah, bees, ants, birds, fish, etc. This has motivated researchers to look further into biological systems, navigation mechanisms and sensing capabilities that can be inspired and lead to better ways in the design and implementation of intelligent and autonomous system. Systems synthesis must guarantee an eventual consensus and coherence between behavioral and structural domains, as well as ensure descriptive and integrative features in the design. These can be achieved by applying the evolutionary biological systems developments. A highlight for some of the challenges may include the following,

a) Deep understanding of the diversity and efficiency of structure-function relationships in natural/biological systems at the element/component, subsystems and system levels. The interest lies not just in the abstraction of new and useful ideas from nature but also in the process by which this is done,
b) It is important to understand that nature may evolve different biological mechanisms to solve real world problems in different environments and circumstances,
c) Biological inspiration does not mean that the weaknesses of biology must be adopted along with the strengths,
d) Biological adaptation to a given environment emerge from a natural selection and evolving process that depends on the environment and the entire historical evolution,
e) It is necessary to keep in mind that the relation between understanding of biological organisms and developing engineered solutions is cyclic. Solutions arrived at by natural selection are often a good starting point in the search for answers to problems. The use of a biological metaphor to inspire new approaches does not necessarily imply that the biological side is well understood,
f) When seeking for an effective solution, it is important to identify the needs from engineering side and then try to match them with most effective biologically inspired solution(s) and find-out how best to implement them,
g) Biological systems are multifunctional and they cannot be optimized for any individual function separately. Hence, successful implementation of a particular biological function requires the ability to isolate irrelevant parts that do not contribute to the desired function.
h) Innovative solutions may require to consider the possibility of combining functions from different biological systems,
i) Biomimetic and bioinspiration demand to integrate biological materials and elements with man-made components/modules through bio-interfacing.

.

IV. CONCLUSIONS

By studying and analyzing biological systems, one may be able to derive or understand the relevant principles and use them to help solve engineering problems. However, the main challenge facing the development of biologically inspired actuators is the available technology, materials and the methods of fabrication as it is still in their infancy compared to nature’s evolution. Biomaterials are expected to become the dominant focus of materials research, as it would lead to down-sizing of engineered components and the up-scaling incorporation of biomimetic concepts and processes. Finally, in order to achieve desirable lifelike motion, actuators must be able to reproduce the important features of natural muscle.

REFERENCES

[1] Y. Bar-Cohen, “Biologically Inspired Intelligent Robotics”, In Proceedings of the SPIE Smart Structures Conference, March 2003. Paper 5051-02,
[2] L. D. Paulson, “Biomimetic Robots”, IEEE Computer, 2004, pp. 48-53.
[3] M. K. Habib, K. Watanabe, and K. Izumi, ““Biomimetics Intelligent Robots and Biological Inspiration”, Int. Conf. on Control, Instrumentation and Mechatronics ‘CIM’2007’, Johor-Malaysia, 2007, pp. 824-832.
[4] R. G. Dennis and H. Hugh Herr, “Engineered Muscle Actuators: Cells and Tissues,” In Biomimetics: Biologically Inspired Technologies Edited by Bar-Cohen, CRC Publisher, 2005, pp. 243-266.
[5] D. Popovic and T. Sinkjaer, “Control of movement for the physically disabled,” Springer-Verlag, 2000.
[6] M. H. Dickinson, C.T. Farley, R.J. Full, M.A.R. Koehl, R. Kram, and S. Lehman. 2000. “How Animals Move: An Integrative View,” *Science* 288, pp. 100–106.
[7] J. E. Clark, J. G. Cham, S. A. Bailey, E. M. Froehlich, P. K. Nahata, R. J. Full, and M. R. Cutkosky, “Biomimetic Design and Fabrication of a Hexapedal Running Robot,” In Proceedings of IEEE ICRA’2001, Vol. 4, 2001, pp. 3643–3649.
[8] R. Pelrine, R. Kornbluh, Q. Pei, S. Stanford, S. Oh, J. Eckerle, R. Full, Ma. Rosenthal and K. Meijer, “Dielectric Elastomer Artificial Muscle Actuators: Toward Biomimetic Motion,” In SPIE Conf. Proceedings, Smart Structures and Materials 2002, Vol. 4695, 2002, pp. 126-137.
[9] S. Ashley, "Artificial Muscles", Scientific American, 2003, pp. 52-59.
[10] A. M. Anderson, K. Streitlien, D. S. Barrett and M. S. Triantafyllou, “Oscillating Foils of High Propulsive Efficiency,” Journal of Fluid Mech, Vol. 360, 1998, pp. 41-72.
[11] Unver, A. Uneri, A. Aydemir, and M. Sitti, ”Geckobot: A Gecko inspired climbing robot using dry adhesives,” In Proceedings of the IEEE ICRA’2006, 2006, pp. 2329-2335.
[12] Funakubo, H. (ed.) Shape Memory Alloys. Gordon and Breach: New York, 1987.
[13] I. W. Hunter, S. Lafontaine, J.M. Hollerbach and P.J. Hunter, “Fast reversible NiTi fibers for use in microrobotics,” Proceedings IEEE Micro Electro Mechanical Systems, 1991, 2, 166-170.
[14] K. Ikuta, “Micro/miniature shape memory alloy actuator,” Proceedings IEEE Micro Electro Mechanical Systems, 1990, 3, 2156-2161.
[15] T. M. Kubow and R. J. Full, “The Role of the Mechanical System in Control: A Hypothesis of Self-Stabilization in Hexapedal Runners,” Philosophical Transactions of the Royal Society of London Series B-Biological Sciences, Vol. 354, No. 1385.1999, pp. 849–861.
[16] J.N. Barisci, G.M. Spinks, C.C. Wallace, J.D. Madden and R.H. Baughman, “Increased actuation rate of electromechanical carbon nanotube actuators using potential pulses with resistance compensation,” Smart Materials and Structures, 2003, Vol. 12 , No. 4, pp. 549-555.
[17] G. Gu, M. Schmid, P.-W. Chiu, A. Minett, J. Fraysee, G.-T. Kim, S. Roth, M. Kozlov, E. Munoz & R. Baughman, "V2O5 nanofibre sheet actuators," Nature Materials, 2003, Vol. 2, pp. 316-319.

© ISAROB 2012