Biomimetics and the Application to Devices

Morley Stone
Air Force Research Laboratoyr
Wright-Patterson Air Force Base, Ohio

1. **Biology and Engineering – Introduction to Biomimetics**

At first glance, imitating nature via biomimetics seems to be a straightforward proposition. For example, if one is a roboticist, just add legs to the platform instead of wheels. Unfortunately, and as often the case, the devil is in the details. This short synopsis will cover biomimetic examples of material synthesis, sensing and robotics. This overview will attempt to capture some lessons learned, some surprising and unanticipated insights, and some of the potential pitfalls encountered along the way.
For a more complete review, recent perspectives on combining biology with other disciplines have recently been published[1].

"Just DON'T add water"

Often, biologists and engineers speak two completely different languages. This is perhaps no more graphically illustrated than comparing the world of electrical engineers and sensor designers with the world of biology. Manipulation of biological macromolecules, i.e., nucleic acids and/or proteins, means the use of buffered solutions (usually pH ~ 7), controlled salinity, and regulated temperatures. Incorporating these biological salt solutions with electronics and sensor architectures seems to be an oxymoron. Thus, the conversion or push of biological materials away from solution to solid-state processing has been a key technology driver within our lab.

The key to overcoming this seemingly insurmountable incompatibility is the use of "bridging" materials systems. From our work, this has been the use of polymer host materials to capture and maintain the biological functionality[2]. Many polymer systems qualify has hydrogels because they incorporate and maintain an enormous amount of water, e.g., poly(vinyl alcohol) (PVA). While the biological side of this equation is satisfied via the incorporation of water, polymer systems can be spin-coated, lithographically patterned, made conductive, and a host of other treatments that electrical engineers routinely use. Thus, polymers represent a truly bridging material system in making biological macromolecules mesh with synthetic technology.

Another recent example highlights the potential biological materials can have when integrated into a common electrical construct like a light emitting diode (LED). However, this work requires a paradigm shift in materials thinking — namely what would happen if DNA were no longer processed on traditional microgram quantities, but processed in gram and kilogram quantities. The fishing industry in Japan processes tons of seafood yearly. In conjunction, they also throw away tons of DNA from fish gametes every year. Researchers at the Chitose Institute of Science and Technology in Japan, in partnership with our laboratory, have processed this discarded DNA into a surfactant complex and have scaled the process up on a multi-gram scale[3]. At this scale and in this form, the DNA can now be spin-coated into tradition electronics architectures. As recently

[1] Naik R R., Stone M O. (2005) *Materials Today* **8**:18-26.
[2] Brott L L, Rozenzhak S M, Naik R R, Davidson S R, Perrin R E, Stone M O. (2004) *Advanced Materials* **16**: 592-596.
[3] Wang L, Yoshida J, Ogata N. (2001) *Chem. Mater.* **13**: 1273-1281.

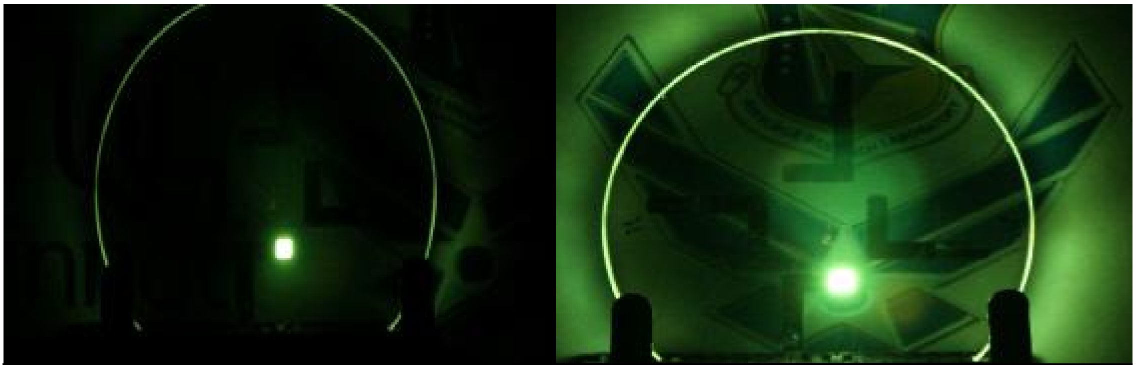

Figure 1: Photographs of Alq_3 green emitting BioLED and baseline OLED devices in operation.

published[4], a DNA electron blocking layer spin deposited on the hole injection side of the electron-hole recombination layer greatly enhanced LED efficiency and performance (Figure 1).

"One Step Removed"

In the previous section, the direct incorporation of biological macromolecules was presented. In another approaches, we have attempted to use biology indirectly in advanced material synthesis and devices. Like the refrain from a popular chemical company commercial — biology isn't in the final material, it makes the final material better.

Labs around the world have raced to harness the incredible electronic, thermal, and mechanical properties inherent in single-walled carbon nanotubes (SWNTs). One impediment to harnessing SWNTs is the wide variety of carbon nanotubes produced after a synthesis run. After a typical run, there is a large dispersion of sizes (both in length and diameter) contributing to a variety of chiralities (which dictate the metallic or semiconducting nature of the SWNT). Much of this size heterogeneity arises from the heterogeneity of the starting metallic nanoparticles used to catalyze the growth of SWNTs.

Ferritins and ferritin-like proteins sequester iron (in the form of iron oxide) in precisely defined cavities ranging from 8 nm to 4 nm for human and bacterial forms, respectively. We recently engineered a bacterial form called DPS to produce uniform, monodisperse iron oxide particles[5]. We reasoned that this monodisperse starting pool of nanoparticles would lead to a more monodisperse population of SWNTs. Indeed, after the bacterial protein was used to produce the iron oxide particles, the biological shell was removed via scintering in a reduced atmosphere and subjected to gas-phase carbon nanotube growth. The resulting SWNTs adopted the monodisperse character of the starting catalyst particles; thus, biology wasn't in the final product, it was used to make a technologically promising material better.

2. Materials Science and Engineering Overlapping with Biology

From a materials science and engineering perspective, favorable properties, i.e., electronic and structural, usually emerge when one has control over the synthesis process at finer and finer levels, hence the frenzy and hype over nanotechnology. As illustrated above in the carbon nanotube example, biology can give us tools to control and/or synthesize materials with molecular-level control.

A powerful illustrative example of this control comes from unicellular algae, called diatoms, which make exquisite cellular structures out of silica. Thousands of species of diatoms exist in salt and fresh water. Each diatom species makes unique silica structures and patterns – from hinges to intricate arrays of holes and spines. This intricate and precise silica synthesis occurs at

[4] Hagen J A, Li W, Steckl A J, Grote J G. (2006) *Appl. Phys. Lett.* **88**: 171109-171111.
[5] Kramer R M, Sowards L A, Pender M J, Stone M O, Naik R R. (2005) *Langmuir* **21**: 8466-8470.

ambient temperature and pH and possesses a complexity greater than anything we can make synthetically using sol-gel techniques.

The work of Kröger and colleagues provided molecular insight into the silica deposition process of diatoms[6]. This insight has allowed us to ask questions about the molecular evolution of this activity ***de novo***[7], and how to apply this activity to accomplish practical applications, i.e., enzymatic encapsulation[8].

From this activity, and the work of others, the field of biomineralization has been able to greatly broaden the scope of materials synthesized via a biological route to encompass not only oxides, but also metals and semiconductors[9]. When one considers the fact that peptides specific for inorganic binding and nucleation can be combined, i.e., genetically fused, with peptides that bind another moiety, endless possibilities begin to emerge. This opens the possibility of directly incorporating biological macromolecules directly into electronic structures/devices. For example, one could imagine literally growing a field effect transistor (FET) metal-oxide-metal architecture via a biological route rather than relying upon standard top-down photolithographic processes. Additionally, this route does not just possess electronic possibilities but new approaches in optics and catalysis. Recently, we have shown that by growing bi-metallic systems using a bio-based approach, enhanced catalytic activity of such bi-metallic materials can be demonstrated[10].

3. Bio-Inspired Robotics: Applied Biology and Engineering

The combination of biological principles with mechanical engineering and robotics has opened entirely new areas and possibilities[11]. Starting with the premise "Why do legs matter?" the field is exploding to encompass why materials properties matter, why mechanics and architecture matter and how biological insight can give us completely new capabilities. Entirely new lessons and robotic capabilities have emerged – dynamic compliance, molecular adhesion, conformal grasping, and dynamic stability – to name just a few of the concepts implemented into robotic platforms.

The first contributions of biology to robotics came from the insight and advantages afforded by a sprawled posture and the ability to utilize opposing forces to achieve self-stabilization[12,13]. Much of this early work focused on understanding the proper mechanics involved in legged locomotion. The spring-loaded inverted pendulum (SLIP) model has been accepted as an accurate model of biological locomotion independent of the number of legs or the biological platform, i.e., horse or human or cockroach.

Recently, the Cutkosky lab at Stanford, who developed pneumatically-driven hexapod running robots, has been challenged to build a wall-climbing platform capable of emulating gecko-like behavior[14]. From a materials science perspective, the challenge has centered on the ability to produce synthetic hair arrays with a diameter of 200 nm, at a density of 1-2e9 hairs/cm^2, and be self-cleaning.

---

[6] Kröger N, Deutzmann R, Sumper M. (1999) *Science* **286**: 1129-1132.
[7] Naik R R, Brott L L, Clarson S J, Stone M O. (2002) *J of Nanoscience and Nanotechnology* **2**: 1-6.
[8] Luckarift H R, Spain J C, Naik R R, Stone M O. (2004) *Nature Biotechnology* **22**: 211-213.
[9] Slocik J M, Stone M O, Naik R R. (2005) *Small* **1**: 1048-1052.
[10] Slocik J M, Naik R R. (2006) *Advanced Materials* **18**: 1988-1992.
[11] Biodynotics Program, Defense Sciences Office, Defense Advanced Research Projects Agency
[12] Full R J and Tu M S. (1991) *J. Exp. Biol.* **156**: 215-231.
[13] Dickenson M H, Farley C T, Full R J, Koehl M A R, Kram R, Lehman S. (2000) *Science* **288**: 100-106.
[14] Clark J E, Cham J G, Bailey S A, Froehlich E M, Nahata P K, Full R J, Cutkosky M R. (2001) Proceedings of IEEE International Conference on Robotics and Automation, 3643-3649.

Aside from this challenge, the robotics field could benefit immensely from having tunable (dynamic) modulus materials. Today, compliance is usually tuned mechanically. The cost in weight in power is expensive; in addition, the capability afforded by this tuning is lacking compared to the desired performance. Biology possesses numerous models of tunable modulus materials, e.g., the sea cucumber, and extrapolating these lessons to robotics could have a huge impact.

4. Concluding Remarks

Within our research labs, we are framing our future investments in an area we term biotronics. We use this term to encompass both bio-electronics and bio-photonics. As can be seen from the LED and FET examples above, this area is ripe for revolutionary breakthroughs afforded by biological material incorporation. New capabilities, like tunable dielectrics, could revolutionize how we perform sensing and electronic readout. It is our vision that a new integrated package of sensing and readout will emerge.

Also highlighted is the ability that biology gives us to fabricate materials, structures, and devices from the bottom-up. Many believe that if we are truly going to harness commercially viable nano-manufacturing, bio-inspiration is going to play a key role in making this a reality. Catalysis and self-assembly have been mastered by biological systems like enzymes and viruses, respectively. Lessons are coming from these areas and being applied to traditional solid-state electronics fields. The engineering fields are beginning to realize the possibilities and it is of paramount importance that we begin to institutionalize this in our undergraduate and graduate training programs. Numerous countries are awaking to this realization and the future technical base of the country is dependent upon the science and engineering departments of this country fostering this interdisciplinary training.