BIOMIMETICS: NEW TOOLS FOR AN OLD MYTH

Danilo De Rossi and Arti Ahluwalia

Centro Interdepartimentale di Ricerca "E.Piaggio", Facoltà di Ingegneria, Università di Pisa, via Diotisalvi 2, 56126 Pisa, Italy – Tel +39 050 553639, Fax ...550650, Email: derossi@piaggio.ccii.unipi.it, Arti.Ahluwalia@ing.unipi.it

Abstract **– A recent Vth Framework call for proposals *Neuroinformatics for "living artefacts"* is focused on *basic research on systems that possess properties akin to those of living organisms to explore new synergies between Neurosciences and Information Technologies.* This is evidence of the growing awareness amongst scientists and more significantly, politicians, of the importance of basic research in the field of biomimetics in order to help us better understand the world around us, as well as a stepping stone to improving the man-technology interface. The purpose of this keynote lecture is to lead you along new avenues which combined with state of the art materials science and microfabrication technologies, could provide the key to creating truly biomimetic systems that are capable of dynamic growth, self organisation and possess sensory motor mechanisms.**

1. INTRODUCTION

The increasing importance given to quiet, clean, environmentally sound and small yet powerful machines has spurred a number of engineers to seek new directions, away from the classical approaches which have upto now produced deterministic macro engines, composed mainly of inorganic materials. Biomimetists are engineers, who, for want of a better model, aspire to emulate different aspects of life in order to realise useful devices. In the past, several biomimetists have tended to discretise life into what are believed to be its simpler elements, and very little has been done to integrate more than one or two of the characteristic properties of living entities to produce "devices". With our existing technology and know-how, the engineering of truly biomimetic structures is now within our reach, requiring only the input of a vivid imagination and the desire to experiment with the inquisitiveness of a child and with a very multidisciplinary approach.

Although, it may not be necessary to mimic living organisms in their entirety, it is useful to keep in mind the multitude of properties that they possess. Among these are:

Growth by intussusception
Entropy reducing
Movement
Metastability
Sensory-Motor mechanisms
Parsimonious chemistry
Learning and adaptation
Self replication
Evolution
Self destruction
Unpredictibility
Memory
Multi-material construction
Complexity
Softness
Redundancy
Imprecision

Firstly, (following in the footsteps of our fellow engineers!), let's try and "discretise" the components of a biomimetic system. Like living organisms, a biomimetic system should posses an underlying scaffold for mechanical support. The scaffold can be static (for short timescales we can take bone to be a static structure), or exhibit temporal dynamics, such as in the case of bioerodable polymers (if we consider longer times). Superimposed upon this is a dynamic pattern produced by appropriate materials, constantly changing, evolving, in what appears to be a chaotic manner (here we are mimicking for example respiration, or blood flow). Together, this structure, pattern and periodicity establishes a purpose, or function to the system, giving it a "raison d'etre".

2. MICROFABRICATION TECHNOLOGIES AT HAND

Nature has been constructed, starting from a microscopic level, piecemeal, into organisms as small as viruses, or as large as whales. The beginnings are small and each detail has been exquisitely programmed to produce a functional whole. What are the principles of this assembly? What is the unified theory of life? Unfortunately, our level of knowledge about living systems is still at a very primitive level. What we do know is that in biology, structure and function are intimately bound together, so the basic underlying structure plays a vital role in determining the nature of the resulting phenotype. We have today dozens of technologies that are capable of constructing microscale scaffolds that could form the basic structural architecture for our "living artefacts.. With these deterministic tools, we can establish a basic guided framework upon which we can allow dynamic systems to take over and evolve into lifelike artefacts.

3. NEW TOOLS: MICROFABRICATION

There are several promising new technologies that could be exploited to produce static predetermined structures. The most well know perhaps is that pioneered by the Mechanical Engineering Group of MIT, known as 3DP [1]. In this method the polymer or ceramic powder is spread on a plate, and the solvent or binder is sprayed by an ink-jet head onto the powder. The ink-jet head is machine driven and raster scans the plates, depositing binder wherever necessary. Where the binder lands, the powder binds. Successive layers can be built up in this way, and have been used to fabricate 3-D scaffolds for the tissue engineering applications.

Another well known method is that developed by Whitesides at Harvard University [2]. This method called Soft Lithography is based on polydimethoxysilane stamps and self-assembly to produce very high-resolution structures, with depths of a few microns. This method has been used successfully for a wide range of applications.

A recently reported technique is that of laser directed guided writing [3]. Molecules can be made to assemble in particular locations using a technique similar to laser tweezers.

One of the simplest and most versatile techniques for microfabrication is syringe based deposition, which uses a fine capillary needle to deposit microscale patterns of polymers in 2 or 3 dimensions. The syringe is powered by motor driven piston or pressurised gas and this technique has been used for tissue engineering applications as well as to construct microactuators [4].

4. DYNAMIC PATTERNS

Dynamic patterns of various forms, be they optical, chemical or physical, have been around for several centuries. They have been regarded largely as scientific curiosities, with very little to offer in terms of potential applications. This is mainly because they are difficult to model and unpredictable, thus possessing at least two characteristics of life-likeness .

Liesegang rings, for example, are foms of periodic precipitations that manifest themselves in a great variety of diffusive media permeated by suitable reactants [5]. Leduc studied these systems extensively, preparing artificial cells, osmotic creatures and membraneous precipitation, all made of inorganic compounds, showing almost all the observable attributes of living creatures [6]. Unfortunately, his studies on synthetic biology have fallen into obscurity. Another example of dynamic patterning is that of the Belousov-Zhabotinskii reaction, which is one of the closest analogs to a life form known in chemistry, showing growing, changing coloured concentric rings which look like a bacterial culture [7]. The similarity between dynamic patterns and the multitude of oscillating biological subsystems is astonishing. Examples are glycolysis, heartbeats, growth rings, butterfly wings and fish stripes [8].

4. NEW TOOLS: MATERIALS

To overview the science of new materials, and new uses of old materials would be a lecture in itself. For the sake of brevity, we will focus on a single class of smart materials: conducting polymers. Conducting polymers (CP) have only recently been used for sensing and actuation. As sensors, they are extremely versatile, since their chemistry can be easily altered by changing pendant groups and dopants. CPs have been utilised in artificial olfaction systems, in which array based sensors are used to discriminate odours in much the same way as the nose. As actuators, CPs have been shown to possess very high force generation capabilities. π- electron conjugated polymers can exert tremendous forces, hundreds of times greater than those of muscles. In film form, given that CPs are rather solid and compact, response times are rather slow, but their electro-mechanical transduction is fairly efficient with typical conversion coefficients of about 1 cm/volt. To render a polymer conductive, it needs to possess charge carriers which can be created within the polymer by reaction with a reagent with redox properties, or by electrochemical oxidation. Polypyrrole is one of the most well studied conducting polymers, and can be oxidised by a variety of agents, such as the ruthenium bipyridyl complex, Ru(bpy), which is a light sensitive reagent used as a catalyst in the light sensitive variant of the Belousov-Zabotinskii reaction [9].

5. MICROFABRICATING THE MYTH

Having talked about the material, the method and the pattern, we can get to the point: guided in situ chemistry to form structural architectures capable of supporting dynamic chemical reactions which can transduce energy input into the system into a purpose or a function. Our thought experiment starts with microfabrication tools, such as a syringe based deposition system, to pattern a gel system of chemical lenses, gratings, pinholes and fibers to form a basic structural, and perhaps functional framework with opto-chemical pathways. The chemical pathways can be formed by site specific crosslinking of a polymer such polymethymethacrylate using a second syringe for example. Upon the addition of reactants which diffuse through the gel characteristic periodic precipation patterns (such as a bromate salt) are produced. This can form a spatial pattern (static in time) over the static scaffold, and be used to modulate the spatial structure of the system. By "feeding" the system with pyyrole monomers well as the reactants of the BZ light sensitive reaction, the pyrrole polymerises and deposits in the areas of the bromate precipitate in the presence of light. Thus, in this system, polypyrrole is cyclically oxidised and reduced, with photons as a modulator of this cycle. The periodic redox reaction also produces oscillatory light modulated movement, due to chemo-mechanical transduction in the polymer. So, in our thought experiment, this system possess sensory-motor properties, is soft, unpredictable, complex and may also incorporate other lifelike properties.

Given that living systems are unpredictable by nature, it is impossible to say what this synthetic system is capable of "doing". Wouldn't that be like asking "what is the purpose of life?"

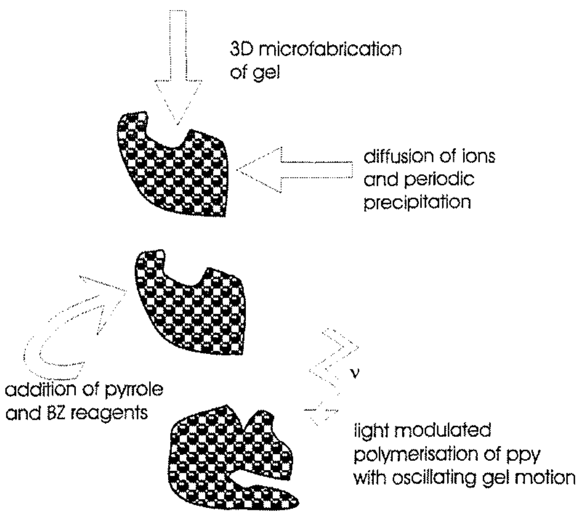

Figure 1: Essential steps for the fabrication of a lifelike system with static and dynamic patterning and sensory-motor responses.

REFERENCES

1. R.A. Giordano, B.M. Wu, S. W. Borland, L.G. Cima, E. M. Sachs, M. J. Cima, "Mechanical properties of dense polylactic acid structures fabricated by three dimensional printing", *J. Biomaterial Sci. Polymer Edn.*, vol. 8, , pp.63-75,1996.
2. R. S. Kane, S. Takayama, E. Ostuni, D. E. Ingber, and G.M. Whitesides, "Patterning proteins and cells using soft lithograpy", *Biomaterials* vol. 20, pp. 2363-2376,1999.
3. D.J. Odde and M.J. Renn,, "Laser-guided direct writing for applications in biotechnology", *Tibtech*, vol.17, pp.385-389, October 1999.
4. G.Vozzi, A. Ahluwalia, De Rossi, and A. Sapienza "Deposition of 2 and 3-D Polymer Scaffolds with a Well Defined Geometry for Application to Tissue Engineering", submitted to Tissue Engineering.
5. H.K. Henish, "Crystals in Gels and Leisegang Rings", Cambridge University Press, Cambridge, 1988.
6. S. Leduc, "Theorie Physico-chimie de la Vie et Generation Spontanèes", A.Poinat, Paris 1910.
7. A.T. Winfree, "The Geometry of Biological Time", Springer-Verlag, Berlin, 1990.
8. S. Kondo and R. Asai, Nature," A reaction diffusion wave on the skin of the marine angelfish Pomacanthus", vol. 376, pp.765-768, 1995.
9. L. Kuhnert, K.I. Agladze, and V.I. Krinsky, Nature, "Image processing using light sensitive chemical waves", vol.337, pp. 244-247, 1989.