BIOCOMPONENTS

BRINGING LIFE TO ENGINEERING

Vegetation may improve indoor environments through the removal of particulates and airborne toxins, plus the cooling and humidifying effects of evapotranspiration © Source: Andrew Eland www.andreweland.org

Ingenia welcomes the opportunity to introduce a new term and a novel perspective: 'biocomponent' engineering. The authors, Peter Moar and Professor Peter Guthrie OBE, explore the implications of using living organisms as components within engineering.

The terms 'bioengineering' and 'biotechnology' encapsulate a broad swathe of scientific research and engineering practice. For the most part, these involve the application of engineered components, tools and processes to biological systems, for example genetic modification in plants and joint replacement in humans.

However, this relationship may be reversed. It is possible to examine the use of living organisms as components or tools *within* engineering solutions. What then emerges is a range of less familiar, but perhaps equally important, applications.

The former perspective brings engineering to life, the latter brings life to engineering. This article explores the latter perspective in an effort to highlight some exciting research and practice, and to examine its implications for the engineering profession.

NEW LABEL

In seeking to introduce this topic, the authors' first challenge was terminology. What are we to call this subset of bioengineering? Given the absence of any known convention, we have adopted the label 'biocomponent engineering'. Although not unambiguous, this term at least enables an efficient discussion of the topic.

We might tentatively define 'biocomponent engineering' as: engineering solutions deriving functionality from the physical or behavioural characteristics of a living organism, the degree of integration being such that the death or removal of the organism disables, in whole or part, the solution by which it is employed.

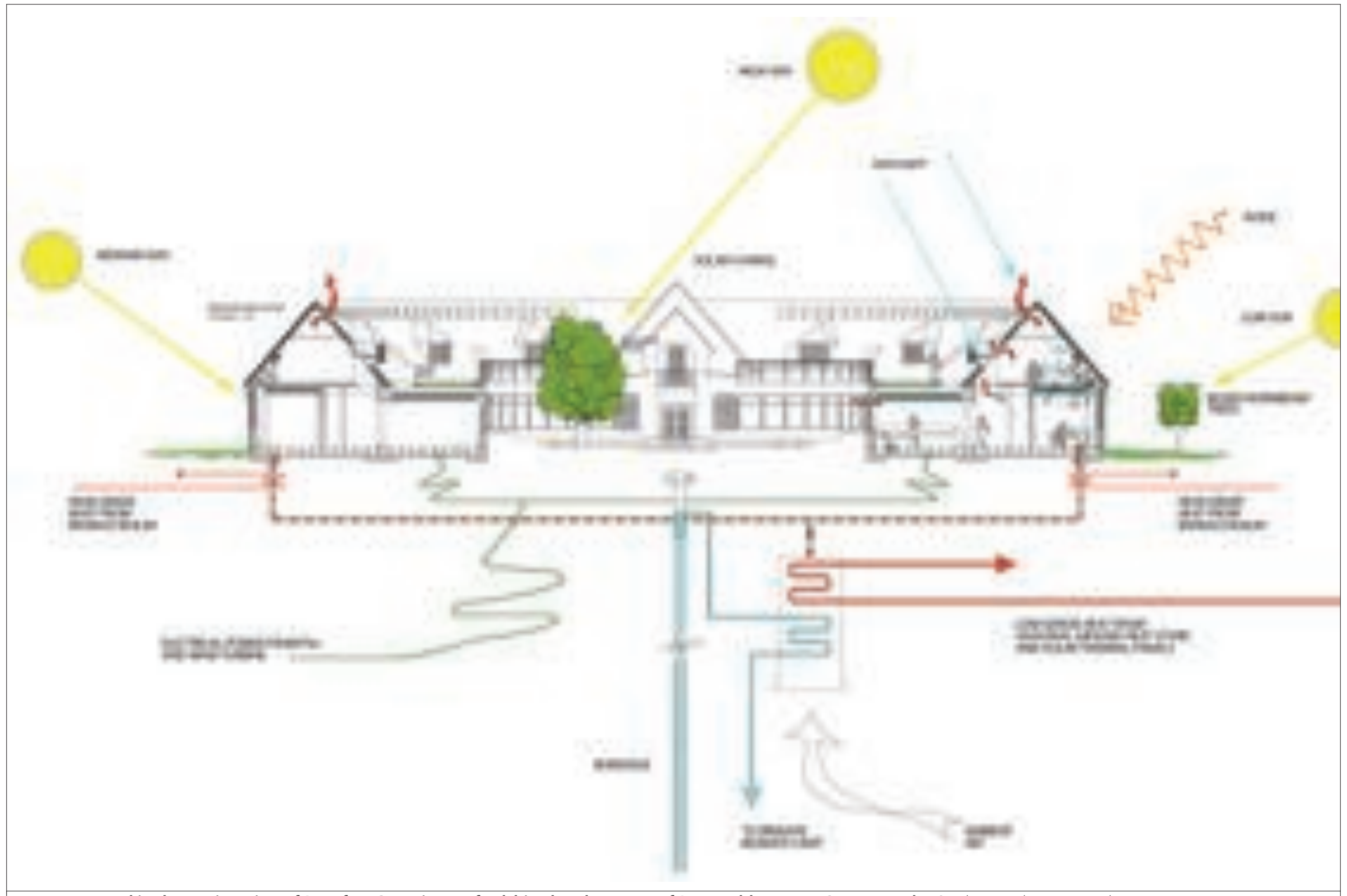
This is not a new perspective. In 1971, for instance, Howard T Odum, a proponent of 'living machines', noted that: "The inventory of the species of the earth is really an immense bin of parts… A species evolved to play one role may be used for a different purpose in a different kind of network as long as its maintenance flows are satisfied." (*Environment, Power, and Society*, Wiley-Interscience, New York).

Historically, biocomponents have tended to precede the development of more effective and sophisticated engineering solutions; horsepower succeeded the horse, for example. Biocomponents could therefore be perceived as interim solutions pending the arrival of superior, non-organic technologies. However, a key point arising from the examples presented below is that each may be viewed as a substitute, rather than a precursor, for 'hard' engineering.

Biocomponents may be drawn from many species, though plants and micro-organisms predominate. A representative selection of applications will be described, grouped into four 'sources' of functionality: roots and shoots; the plant rhizosphere (root/soil zone); micro-organisms, primarily bacteria, fungi and algae; and all other species.

ROOTS AND SHOOTS

Engineering goals can be achieved by the strategic planting of vegetation. Mature deciduous trees, for example, may be positioned to reduce air conditioning and heating loads in buildings, shading south-facing windows from the summer sun, enabling solar



Trees were used in the engineering of Beaufort Court in Hertfordshire, headquarters of Renewable Energy Systems Ltd © Studio E Architects, London

warming once the leaves have fallen. A row of substantial vegetation on the windward side of a building also creates a thermal insulation zone. Meanwhile, understanding the aerodynamic effects of trees has informed planting designs in America's Midwest in order to control the drifting of snow near highways and other infrastructure.

One species of particular interest to engineers is vetiver (*Vetiveria zizanioides*), labelled a 'miracle grass' because of its extraordinary performance characteristics. These include extensive, fast-growing roots with a tensile strength one-sixth that of mild steel. Vetiver roots reach up to four metres below the surface within 12 months, providing a firm anchor for slope stabilisation and erosion control. Vetiver is also tolerant of temperature extremes (-15 to 56°C), acidity, alkalinity, sodicity and heavy metals. Consequently, vetiver has many applications, including the remediation of toxic mine tailings, absorbing their contents while providing surface stabilisation.

Many other plants have been identified for their phytoremediation (or bioremediation) properties. Those classified as 'hyper-accumulators' draw pollutants from the earth without ill effect. These plants are then harvested for safe disposal. One remarkable hyper-accumulator, the tree *Sebertia accuminata*, is able to absorb vast quantities of nickel; 37kg recorded in one example.

The benefits of indoor plants are also proven, including their potential for cooling and humidifying (through evapotranspiration) while collecting airborne particulates on leaves and stems.

RHIZOSPHERE

Much of the useful functionality we observe in plants is performed not by roots and shoots, but by microbial activity within the rhizosphere (the root/soil zone), where living plant matter and micro-organisms (aerobic and anaerobic bacteria) co-exist symbiotically.

Some early discoveries in this field were made by NASA researchers, notably Wolverton, who analysed indoor plant species for their capacity to absorb airborne toxins. Others have followed, often driven by the need to understand and improve office environments. 'Sick building syndrome', for example, has been attributed partly to the release of volatile organic compounds (VOCs), such as toluene, benzene and formaldehyde from office furnishings. The research has demonstrated how bacteria within the rhizosphere convert airborne toxins into harmless nutrients for subsequent consumption by the plant. This functionality is employed in the commercial Biowall filtration system (see figures 1 and 2) developed by Air Quality Systems and the University of Guelph-Humber in Toronto. By drawing stale interior air through a vertical plant/rhizosphere wall, it is claimed that up to 90% of VOCs are removed in a single pass.

Micro-organisms are also able to cleanse water. Multi-stage reed bed technologies, for example, exploit bacterial processes in the underwater rhizosphere. The visible part of the reed is relegated to a supporting role, supplying oxygen to its root-dwelling microbes enabling them to mineralise water-borne impurities.

MICRO-ORGANISMS

A micro-organism (or microbe) is defined, quite simply, as any life form invisible to the naked eye. This includes bacteria and many species of algae and fungi. In addition to their rhizospheric roles, described above, microbes have many other technological applications.

In contrast to the Biowall, conventional industrial biofilters force waste gases through compartments of porous material, such as compost or bark, on which populations of bacteria and fungi are present. Meanwhile, an innovative biofilter undergoing tests at the Massachusetts Institute of Technology (MIT) circulates polluting flue-gases through water-borne algae (eg *Dunaliella parva*) in clear tubes sited on the roof of a university building. The algae use photosynthesis to convert CO_2 in the gases to harmless organic material.

Bioleaching (or biomining) operations employ micro-organisms to recover metals from minerals. One particularly effective bacterium, *Acidithiobacillus ferrooxidans*, obtains energy from the oxidation of ferrous iron and elemental sulphur. A typical bioleaching operation converts insoluble sulphides of metals into soluble metal sulphates, enabling recovery from solution. Bioleaching is a slow, but energy-efficient process, perfectly suited to metal recovery from low-grade ore. In Chile alone, 400,000 tons of copper are biomined each year.

Figure 1. Biowall at the University of Guelph-Humber, Toronto. The wall was built by Air Quality Solutions Ltd. Building by Diamond and Schmitt Architects Inc in joint partnership with RHL Architects Source: Alan Darlington

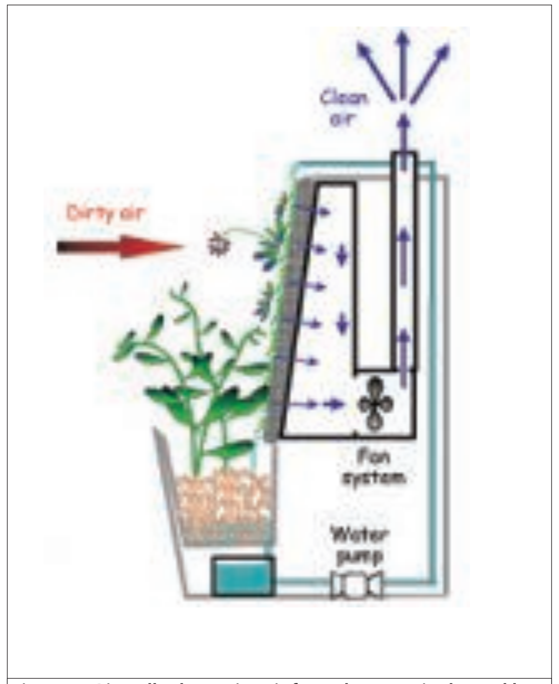


Figure 2. Biowall schematic. Air from the room is cleaned by drawing it through the wet plant-covered surface. The clean air is then returned to the room Source: Alan Darlington

Bacteria also have an important role to play in energy production. Biogas (methane), for example, is produced by fermentation processes within anaerobic digesters. Meanwhile, the heat generated by bacterial activity in compost can be recovered in the form of hot water.

One possible future energy source is the bacterial battery or microbial fuel cell, which harvests electrons produced during bacterial metabolism. Figure 3 illustrates a simple, proven design. It is speculated that, given the reproductive capabilities of bacteria, long-life devices may be feasible.

A valuable characteristic of living organisms is that they respond in real time to environmental conditions. This functionality is exploited in bioreporters, or 'laboratories on chips'. A bioreporter interprets and quantifies the chemical responses of an onboard living organism (*E. coli* for example), offering the prospect of low cost, low energy, real-time monitoring for environmental threats, such as irradiation and toxins.

Unlike bacteria, which have long been exploited for technological ends, the engineering value of diatoms has only recently emerged. Diatoms are unicellular algae which internally assemble silica particles into distinctive 3D shell structures, or frustules, with fine features of between 10 and 100 nanometres in scale. Diatoms reproduce rapidly. Consequently, they have attracted the attention of nanotechnologists with their potential to manufacture, in massive quantities, templates for nanoscale engineering components. Figure 4 illustrates the diversity of diatom shell structures.

OTHER ORGANISMS

In the interests of space, the use of higher life forms such as birds and mammals will not be discussed here. However, some primitive life forms, although too large to be classed as microbes, have also been successfully employed by engineers.

A recent example emerged in 2006, when a team from the Universities of Southampton and Kobe revealed a six-legged robot (see figure 5), remarkable for the fact that it was controlled, in part, by the slime mould *Physarum polycephalum* (a large, multi-nuclear cell). The mould responds physically to environmental stimuli, such as light.

The robot was able to translate these responses to leg movements. This represented an important achievement, because such adaptive behaviour is a key design challenge within robotics.

COMBINED FUNCTIONALITY

Some biocomponent solutions combine the functionality of many life forms. For example, the 'living machines' designed by John and Nancy Todd, of Ocean Arks International, employ many of the technologies described above. These engineered ecosystems consist of water tanks, linked in series, populated by plants, microbes, fish, insects and snails. They deliver not only purified water and air, but also cooling by evapotranspiration, food and energy. A number of living machines are now in operation, including a recent implementation at the El Monte Sagrado resort in New Mexico.

More familiar to UK readers are 'green roofs'. The substitution for conventional roofing by a substantial layer of soil and vegetation is becoming a popular design feature. Green roofs increase the service life of the building fabric, protecting it from erosion, UV damage and temperature variations. Rain water is captured, partially cleansed and released at a more manageable rate for public utilities, while the organic layer provides insulation in low temperatures and evaporative cooling when hot.

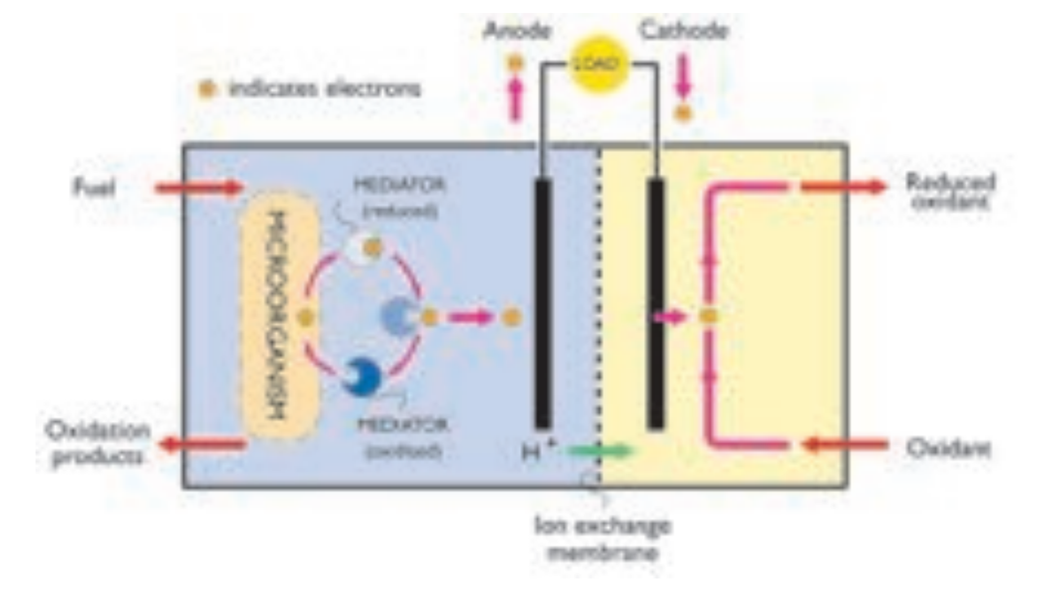


Figure 3. Microbial fuel cell Source: Dean Madden, University of Reading and the National Centre for Biotechnology Education

SCOPE AND EXCLUSIONS

This text has focused specifically upon *living* organisms: those which metabolise, develop and die. Biocomponent engineering, as defined here, excludes the use of organic entities devoid of these characteristics.

For example, recent developments within biomolecular computing, involving the use of recombinant DNA to perform massively parallel computations, are outside the scope of biocomponent engineering. In contrast, the development of genetically modified bacteria to perform computations using the regulatory feedback systems of cellular metabolism, as proposed by John H Reif of Duke University, is clearly valid.

MIT Media Lab's construction of a swimming robot powered by frog muscles (electrically stimulated), though fascinating in itself, is also out of scope. After all, engineers have used non-living biological components for millenia (eg wood, hides and bone). If the label is to retain any meaning at all, it must avoid associations with entities incapable of independent existence.

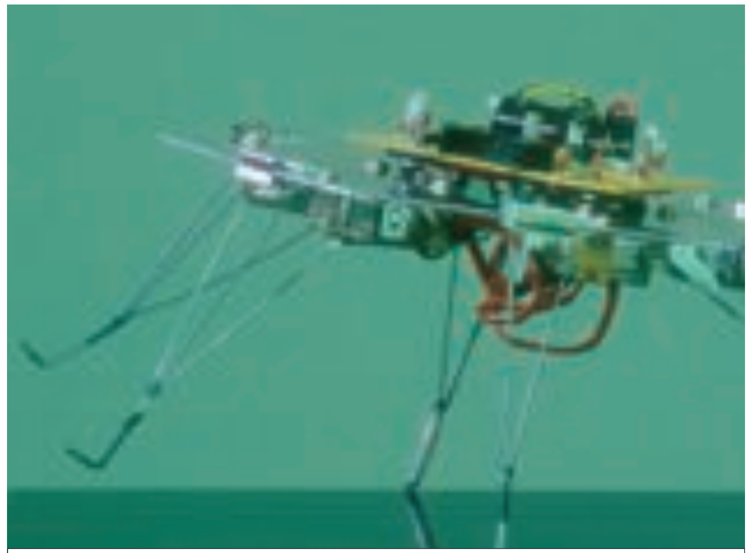
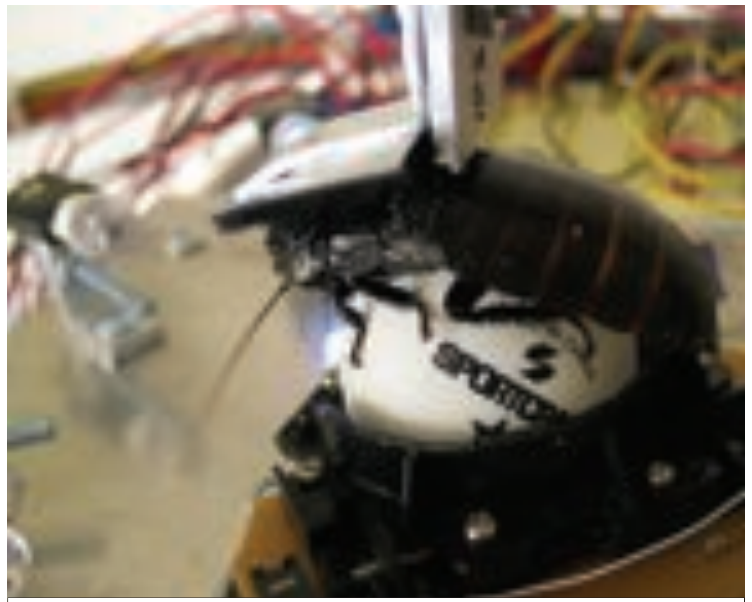


Figure 5. Robot controlled by *Physarum polycephalum* Source: Klaus-Peter Zauner, University of Southampton



The integration of a live cockroach within this robotic device inevitably raises ethical questions about the use of living organisms by engineers Source: Garnet Hertz www.conceptlab.com

Figure 4. Diatom nanostructures. There are tens of thousands of diatom species, each characterised by a unique frustule shape; see the book by Round et al, referenced at the end of this article, for an extraordinary set of detailed electron microscope images Source: Alfred-Wegener-Institute/Friedel Hinz

BENEFITS

In addition to their functional value, biocomponents dovetail nicely with the drive for environmental sustainability. Organic components reduce dependence upon conventional engineering materials, which are frequently obtained from non-renewable resources. Organisms are, of course, biodegradable, renewable and carbon-neutral.

Living organisms derive their energy primarily from the sun, whereas conventional engineering materials often possess significant quantities of embodied non-renewable energy (from manufacturing and transportation). Furthermore, electro-mechanical components consume non-renewable energy throughout their operational lives.

Where vegetation is used outdoors, biodiversity is supported; in urban environments plants help to mitigate the 'urban heat island' effect. Biocomponents are also inexpensive, with most species being freely available. Finally, living organisms are capable of self-repair. This characteristic is an important differentiator for biocomponents, theoretically increasing both design life and reliability.

ISSUES ARISING

The perception of living organisms as tools of the engineering profession raises ethical questions about the manipulation and exploitation of species. This applies particularly to the pursuit of genetically-modified components – an inevitable development in the quest for efficiency. Meanwhile, the importation of superior biocomponents from overseas could result in non-native species overwhelming local populations.

On a more practical and professional level, living organisms possess characteristics which are alien to engineers: they are relatively unpredictable, of imprecise dimensions, often slow-growing and susceptible to disease. Biocomponents therefore challenge engineers to think outside their traditional cognitive realm.

More generally, there is a well-documented skills gap at the interface of engineering and biology which probably hinders the pace of biocomponent development and innovation. Furthermore, funding for research at this interface needs to bridge the 'silos' created by disciplines which are often physically separated and assessed individually for financial support.

Biocomponents: summary table

Source of functionality	Biocomponent applications: examples	Some conventional alternatives
Plant roots and shoots	deciduous shading evaporative cooling humidification hyper-accumulation insulation zones particulate collection slope stabilisation snow drift management	air conditioning; heating; blinds air conditioning; electric fans air conditioning; electric humidifiers physical removal; chemical and thermal solutions heating; insulation materials electro-mechanical filters pinning; piles manufactured snow fences
Plant rhizosphere (root/soil zone)	air purification water purification	air conditioning; electro-mechanical air scrubbers chemicals; manufactured filters
Micro-organisms (bacteria, fungi, algae)	bacterial battery biofilter biogas bioleaching bioreporter cellular computing compost heat nanostructure manufacturing	non-renewable energy sources electro-mechanical air scrubbers non-renewable energy sources smelting chemical sensors semiconductors non-renewable energy sources no precedents; solutions would be energy-intensive
Other organisms	robotic control (adaptive)	probably digital or chemical
Combined	green roofs living machines	higher capacity drainage; insulation materials etc air conditioning; chemicals; manufactured filters etc

THE SEEDS ARE SOWN

The authors claim no expertise in biocomponent engineering, merely a desire to highlight its potential for delivering new technologies, plus a number of social and environmental benefits. This article has presented a representative selection of applications which, in our opinion, exemplify an important perspective upon the design of engineering solutions. It has been demonstrated that living organisms may be successfully deployed as engineering components, often presenting a serious alternative to more conventional materials, tools and processes.

Ethical, cultural, training and funding issues aside, one could argue that further biocomponent innovation is constrained only by the ingenuity of engineers.

Further reference

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Sandhage, Kenneth H et al, *Merging Biological Self-assembly with Synthetic Chemical Tailoring: The Potential for 3-D Genetically Engineered Micro/Nano-devices (3-D GEMS)*, International Journal of Applied Ceramic Technology, 2005, Vol 2, No 4, pp 317–326.
Vetiver knowledge networks:
http://prvn.go.th
www.vetiver.com

BIOGRAPHIES – Peter Moar MPhil MSc BScEcon and Professor Peter Guthrie OBE

Peter Moar is a Visiting Researcher in the University of Cambridge Engineering Department. He is a graduate of the Universities of Wales, London and Cambridge, most recently completing Cambridge's innovative MPhil in Technology Policy.

Peter designed and maintained databases for General Electric Corporation between 1997 and 2004. He is now an independent researcher of business and technology issues.

Peter Guthrie is the first Professor in Engineering for Sustainable Development in the UK, having held this post at the University of Cambridge since 2000. He is a civil engineer and geotechnical specialist with worldwide experience of road, rail and air projects.

Peter has received public recognition for his involvement in technology charities, including the founding of RedR, which provides engineers to disaster relief agencies. He was awarded the OBE in 1994, was Vice-President of the Institution of Civil Engineers in the late 1990s, and received the prestigious Beacon Prize for charitable giving in 2005.