Int. J. Engng Ed. Vol. 22, No. 1, pp. 28–34, 2006
Printed in Great Britain.

0949-149X/91 $3.00+0.00

'Engineering to Biology' and 'Biology to Engineering': The Bi-directional Connection Between Engineering and Biology in Biological Engineering Design*

JOEL L. CUELLO
Department of Agricultural and Biosystems Engineering, The University of Arizona, 507 Shantz Building, Tucson, AZ 85721, USA. E-mail: cuelloj@email.arizona.edu

Biological Engineering, the engineering discipline that connects engineering and biology, encompasses both 'connecting engineering to biology' and 'connecting biology to engineering' in its engineering design process. The first directional case of 'connecting engineering to biology' pertains to the application of the engineering design process to regulate and manipulate a given biological system for the purpose of achieving a desired end. The second directional case of 'connecting biology to engineering' pertains to employing the knowledge of the attributes of biological systems to inform or guide the engineering design of a physical system for the purpose of achieving a desired end. For 'connecting engineering to biology,' the object of the design process is a biological system and its design factors are limited by physicochemical principles. Contrastively, for 'connecting biology to engineering,' the object of the design process is a physical system and its design factors are limited by biological attributes. The first case of 'connecting engineering to biology' addresses the design of: (1) protocol for biological system; (2) structure for biological system; and (3) model for biological system. The second case of 'connecting biology to engineering' addresses the design of: (4) material based on biological system; (5) machine/device based on biological system; and (6) instrument based on biological system.

Keywords: biological engineering; design

INTRODUCTION

MOST OF THE definitions that have been formulated for Biological Engineering—such as that provided by the *Encyclopaedia Britannica*, which defines 'Bioengineering' or Biological Engineering as 'the application of engineering knowledge to fields of medicine and biology' [1]—tend to imply strongly a unidirectional importation of engineering principles into biological systems. What is more, none of the available definitions for Biological Engineering delineate the basic distinction between (1) applying the engineering design process to control and manipulate a biological system (i.e. 'connecting engineering *to* biology') and (2) using the knowledge of the attributes of biological systems to inform the engineering design of a physical system (i.e. 'connecting biology *to* engineering'). Indeed, Biological Engineering, the engineering discipline that connects engineering *and* biology, encompasses both 'connecting engineering to biology' and 'connecting biology to engineering.' The aim of this paper is to help achieve a greater precision in the understanding of the Biological Engineering design process through the following specific objectives:

1. to underscore the two-way or bi-directional connection between engineering and biology in Biological Engineering design;
2. to provide an operational definition for Biological Engineering within each directional case; and
3. to enumerate the problem types for Biological Engineering within each directional case.

A historical overview examining the intersections of the various disciplines through the ages, leading to the melding of engineering and biology in Biological Engineering, has been described by [2].

CONNECTING ENGINEERING TO BIOLOGY

The first directional case for connecting engineering and biology in Biological Engineering design is 'connecting engineering to biology.' This pertains to the application of the engineering design process to regulate and manipulate a given biological system for the purpose of achieving a desired end.

Operational definition

An operational definition for Biological Engineering is a statement of its basic technical activity that is common across its application areas, including

* Accepted 22 August 2005.

the biomedical, biochemical, food, agricultural, ergonomic and environmental areas [3]. An operational definition for Biological Engineering within the context of 'connecting engineering to biology' was provided by Cuello [3] as follows'

> Biological Engineering is the optimization of the performance of a *task* or set of *tasks* performed by a *biological system* through the application of the *engineering design process*.

A *task* is defined as a process or an activity. Examples of tasks performed by a biological system include growth, synthesis, production, assimilation and binding, among others. The doer or performer of the task is known as the *object of the design process*. In the case of 'connecting engineering to biology,' the object of the design process is a *biological system*. A biological system may be defined as a part or the whole of a living entity or a collection of living entities that typically exhibit(s) the processes of growth, respiration, self-regulation and/or self-replication. Examples include a ribosomal RNA, a chloroplast, a bacterium, a colony of bacteria, a multi-cellular organism, etc. The definition of a biological system must include a specification of its organizational level that is relevant in its performance of the desired task or set of tasks. The various organizational levels of a biological system include atomic, molecular, organelle, cellular, tissue, organ, organ system, organismic, population, community, ecosystem and biospheric levels [4].

The *engineering design process* as applied to the optimization of a task or set of tasks performed by a biological system (i.e. 'connecting engineering to biology') is provided with a formal definition as follows (Fig. 1). Given a biological system B (object of the design process), performing a task or set of tasks T, whose performance is represented or measured by a performance index PI (dependent variable), let F_i be a set of all the significant design factors (independent variables) that affect PI. Then, the design function for T for the optimization of its PI as performed by B is:

$$PI_{T,B} = f(F_i)$$

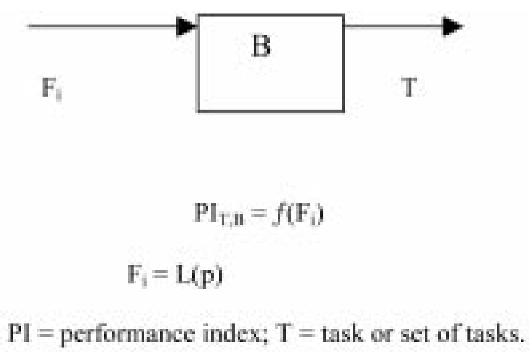

Fig. 1. Biological Engineering design in the case of 'connecting engineering to biology,' where the object of the design process is a biological system (B), and the design factors (F_i) are limited by physicochemical principles (p).

In the case of 'connecting engineering to biology,' physicochemical principles (p) limit the design factors F_i. Examples of p include solubility of a solute in a solvent, mass transfer, energy transfer, momentum transfer, absorptivity, etc. Thus,

$$F_i = L(p)$$

Consider the following illustrative example (Fig. 2), where a photosynthesizing cell culture of *Acmella oppositifolia* is grown to produce a group of polyacetylenes [5].

In this case,

T = production of specific polyacetylenes
PI = productivity (mg polyacetylenes/L of culture—day)
B = *Acmella oppositifolia* cells
F_i = photosynthetic photon flux (PPF), dissolved oxygen (DO), sucrose
p = solubility and mass transfer of oxygen, solubility and mass transfer of sucrose, energy transfer of photons through the culture medium.

Thus,

$$\text{productivity} = f(\text{PPF, DO, sucrose})$$

Also, the design factors would be limited as follows:

$$\text{PPF} = L_1(\text{light transfer through medium})$$

$$\text{DO} = L_2(O_2 \text{ mass transfer and solubility})$$

$$\text{sucrose} = L_3(\text{sucrose mass transfer and solubility})$$

Design process steps

The Biological Engineering design process in the context of 'connecting engineering to biology' consists of the following 10 steps:

1. Identify T.
2. Choose PI for T (e.g. PI = average specific growth rate when T = growth).
3. Define B (e.g. specific microbial cells) and specify its relevant organizational level (e.g. cellular level).
4. Identify F_i corresponding to the chosen organizational level (e.g. oxygen concentration, nutrient concentrations, etc.).
5. Identify the physicochemical principles limiting Fi (e.g. oxygen mass transfer through culture medium).
6. Establish the design function; that is, the relationship(s), which must be at least predictive (quantitative: mathematical or statistical) if not also explanatory (mechanistic), among F_1, F_2, F_3, . . . , F_i and PI.
7. Optimize PI with consideration of design constraints and set the optimal values for F_1, F_2, F_3, . . . and F_i.
8. Verify the results.
9. Adjust, if necessary, the optimal values for F_1, F_2, F_3, . . . and F_i based on the outcome of the verification.
10. Implement the design to perform T.

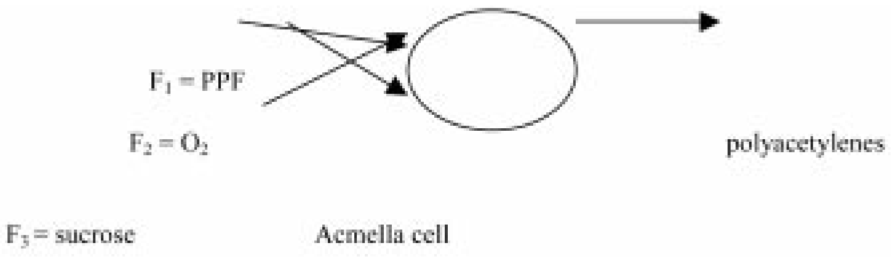

Fig. 2. A photosynthesizing cell of *Acmella oppositifolia* producing a group of polyacetylenes.

Problem types

Regardless of the application areas (biomedical, biochemical, food, agricultural, ergonomic and environmental) in which the engineering design process is employed to optimize the performance of a task or set of tasks performed by a biological system, the engineering design for 'connecting engineering to biology' is always focused on regulating and manipulating the biological system *per se* in such a manner as to optimize the desired task performed by the biological system. This is typically accomplished by regulating and manipulating the *environment* or *milieu* of the biological system. (This, of course, presupposes that the set of genetic characteristics of the biological system is a given. Nothing precludes the set of genetic characteristics of the biological system from also being regulated and manipulated if doing so would help optimize the performance of the desired task.) The three general ways of controlling and manipulating the environment of a biological system constitute the three types of problems that Biological Engineering addresses within the context of 'connecting engineering to biology.' These problem types include:

1. Design of *protocol* for biological systems—This involves setting the optimal levels of the significant environmental factors that affect the performance of the biological system. In some cases, this may involve setting the intensity and duration of exposure and/or the sequence of exposure of the biological system to certain factors. Pertinent applications include biological growth, biological multiplication, biochemical production, biochemical elicitation, bioconversions, microbial decontamination, etc.
2. Design of *structure* for biological systems—This involves designing a physical structure to enable the execution or implementation of the environmental manipulation or control necessary to achieve the desired response from the biological system. Pertinent applications include design of bioreactors (stirred tank, convective flow, ebb-and-flow, etc.) for biochemical production, design of scaffolding to coax cell proliferation and organization for tissue regeneration, etc.
3. Design of *model* for biological systems—This involves constructing a model that establishes the interactions among the biological system in question and the relevant factors (living or nonliving) existing in its environment, and quantitatively predicting the responses of the biological system in question under various scenarios in which the factors assume varying values. Pertinent examples include ecological models predicting the population of a given species under different environmental perturbations, enzyme kinetic model predicting the resulting rates of reaction under scenarios of enzyme inhibition or activation, etc.

Illustrative examples for the three problem types are given in Table 1. Note that each problem type also defines the *output*, or product, of the design process.

CONNECTING BIOLOGY TO ENGINEERING

The second directional case for connecting engineering and biology in Biological Engineering design is 'connecting biology to engineering.' This pertains to employing the knowledge of the attributes of biological systems to inform or guide the engineering design of a physical system for the purpose of achieving a desired end.

Operational definition

An operational definition for Biological Engineering within the context of 'connecting biology to engineering' is provided as follows:

> Biological Engineering is the optimization of the performance of a *task* or set of *tasks* performed by a physical system through the application of the *engineering design process* as informed by the knowledge of the properties, characteristics, traits, structures, principles and/or processes of pertinent or analogous biological systems.

A *task* is again defined as a process or an activity. Examples of tasks performed by a physical system include mechanical support, movement, grasping, sensing, mixing, separation, etc.

In contrast to the first case of 'connecting engineering to biology' in which the object of the engineering design process is a *biological system*, the object of the design process in the current case of 'connecting biology to engineering' is a *physical system*. The specification of a physical system must include a delineation of its size or scale (i.e. macroscopic, microscopic, nanoscopic, etc.).

Table 1. Illustrative examples for the three types of problems that Biological Engineering addresses within the context of 'connecting engineering to biology'

Task	*Design Object*	*Performance Index (Dependent Variable)*	*Design Factors (Independent Variables)*	*Design Factors' Limitations*
1. *Design Output*: protocol				
growth (biological)	specific plant cells	ave. sp. growth rate	nutrient concentrations, PPF level, etc.	energy transfer, mass transfer, etc. (physical)
2. *Design Output*: structure				
production of a chemical	specific microbial cells (biological)	productivity	bioreactor impeller rpm, sparged oxygen vvm, etc.	mass transfer, etc. (physical)
3. *Design Output*: model				
increase population of a species	specific species (biological)	population	drought frequency, food availability, etc.	geography, physical access to food supply, etc. (physical)

The *engineering design process* applied to the optimization of a task or set of tasks performed by a physical system as informed by the knowledge of the attributes of pertinent or analogous biological systems (i.e. 'connecting biology to engineering') is provided with a formal definition as follows (Fig. 3). Given a physical system P (object of the design process), performing a task or set of tasks T whose performance is represented or measured by a performance index PI (dependent variable), let F_i be a set of all the significant design factors (independent variables) that affect PI. Then, the design function for T for the optimization of its PI as performed by P is:

$$PI_{T,P} = f(F_i)$$

Also, in the case of 'connecting biology to engineering,' biological attributes (b) limit the design

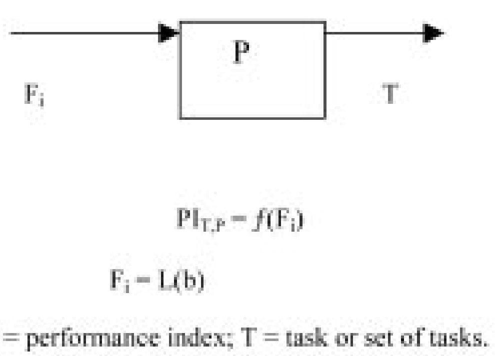

Fig. 3. Biological Engineering design in the case of 'connecting biology to engineering,' where the object of the design process is a physical system (P), and the design factors (F_i) are limited by biological attributes (b).

factors F_i. Again, b may include specific properties, characteristics, traits, structures, principles and/or processes of a biological system pertinent or analogous to the physical system being designed. Thus,

$$F_i = L(b)$$

Consider the following illustrative example, where the relative composition of the aluminum-vanadium alloy Ti-6Al-4V (Fig. 4) was designed so that its modulus of elasticity, the measure of the stiffness of a material, is roughly one-half (110 GPa) of those for 316-stainless steel (200 GPa) and chromium cobalt alloy (227 GPa), and therefore closer to that for the bone, resulting in a more balanced application of load stress at the implant–bone interface [6].

In this case,

T = mechanical support
PI = modulus of elasticity (GPa)
P = artificial replacement bone or joint made of aluminum-vanadium alloy
F_i = aluminum, vanadium
b = modulus of elasticity of human bone or joint

Thus,

$$\text{modulus of elasticity of alloy} = f(\text{aluminum, vanadium})$$

Also, the design factors would be limited as follows:

$$(\text{aluminum} + \text{vanadium}) = L(\text{modulus of elasticity of human bone or joint})$$

Fig. 4. An aluminum-vanadium alloy designed as artificial bone or joint.

Design process steps

The Biological Engineering design process in the context of 'connecting biology to engineering' consists of the following 10 steps:

1. Identify T.
2. Choose PI for T (e.g. PI = compressive strength when T = mechanical support).
3. Define P (e.g. specific composite material) and specify its relevant organizational level (e.g. macroscopic).
4. Identify F_i corresponding to the chosen organizational level (e.g. relative proprotions of component parts, etc.).
5. Identify the biological attributes limiting Fi (e.g. compressive strength of human bone or joint).
6. Establish the design function; that is, the relationship(s), which must be at least predictive (quantitative: mathematical or statistical) if not also explanatory (mechanistic), among F_1, F_2, F_3, . . . , F_i and PI.
7. Optimize PI with consideration of design constraints and set the optimal values for F_1, F_2, F_3, . . . and F_i.
8. Verify the results.
9. Adjust, if necessary, the optimal values for F_1, F_2, F_3, . . . and F_i based on the outcome of the verification.
10. Implement the design to perform T.

Problem types

Regardless of the application areas (biomedical, biochemical, food, agricultural, ergonomic and environmental) in which the engineering design process, as informed by the knowledge of the attributes of pertinent or analogous biological systems, is employed to optimize the performance of a task or set of tasks performed by a given physical system, there are only three general types of problems that Biological Engineering addresses within the context of 'connecting biology to engineering.' These problem types include:

1. Design of *materials* based on biological systems—This involves the design of materials that are meant to simulate or enhance specific attributes of a component of a biological system. Pertinent examples include human prostheses, etc.
2. Design of *machines/devices* based on biological systems—This involves the design of machines/devices that are meant to perform work that is normally performed by a biological system. Pertinent examples include artificial organs, bio-based micro- and nano-electromechanical systems, robots, etc. This also involves the design of machines/devices that perform the task of physically processing (e.g. mixing, separating, etc.) biologically derived materials (e.g. food ingredients, etc.).
3. Design of *instruments* based on biological systems—This involves the design of instruments for the sensing and measuring of specific parameters of biological systems. Pertinent examples include machine vision, artificial nose, etc.

Illustrative examples for the three problem types are given in Table 2. Again, note that each problem type also defines the *output*, or product, of the design process.

Numerous futuristic developments in Biological Engineering lie in this second directional case of 'connecting biology to engineering.' For the most part, these developments focus on endowing machines or devices—from the macro to the nano in scale—with such important biological attributes as the capacities for self-assembly, self-replication and evolution. While the Drexlerian concept of a universal fabricator, a machine capable of building anything including itself atom by atom [7], is considered by most scientists and engineers to be visionary but simply impossible [8], many agree that it is still possible to design self-assembling machines—though not atom by atom, but likely by blocks of molecules—for the simple reason that the capacity for self-assembly is a reality in biological systems. Self-replicating machines, whose biological counterparts also exist, are still currently beyond reach as well. A modicum of progress has been achieved, however, in the design of evolutionary machines through artificial evolution. Artificial evolution is a process through which machines, in their interaction with their environment, adapt and exploit the physics of their interaction with their environment, not only by modifying the software running in their processors, but also by modifying their hardware [9]. Evolution of electronic circuits and evolution of robot bodies constitute the two types of evolvable hardware [9]. Evolution of electronic circuits is based on the recent availability of reconfigurable devices such as the programmable logic devices [10] and the field programmable gate arrays [11, 12]. The first example of an evolved hardware circuit was demonstrated by Thompson [13] in an experiment consisting of evolving a dynamic state machine that was analogous to a reconfigurable circuit with programmable temporal dynamics and which could perform wall avoidance behavior.

Table 2. Illustrative examples for the three types of problems that Biological Engineering addresses within the context of 'connecting biology to engineering'

Task	*Design Object*	*Performance Index (Dependent Variable)*	*Design Factors (Independent Variables)*	*Design Factors' Limitations*
1. *Design Output*: material				
mechanical support	metal alloy (physical)	modulus of elasticity of alloy	relative proportions of alloy constituents, etc.	modulus of elasticity of human bone (biological)
2. *Design Output*: machine/device				
cardiac pacing	pacemaker (physical)	reliability	pulse amplitude, interval, width, etc.	normal cardiac pacing (biological)
3. *Design Output*: instrument				
detect surface blemish	artificial vision (physical)	accuracy	camera resolution, etc.	optical properties of fruit surface, etc. (biological)

Realizing evolvable body structures, however, proves much more technologically challenging [9]. Pollock *et al.* [14] explored the possibility of evolving the structure of physical robots. It is evident that further advances in the novel engineering of materials are necessary to realize the evolution of robot morphology.

It is only fair to mention that exciting developments are also brewing in Biological Engineering's first directional case of 'connecting engineering to biology.' The design of strategies (protocols, structures, models) in tissue engineering to coax groups of cells to proliferate and organize themselves into functional tissues or organs (think of a factory for human organs) is just as futuristic as the other applications previously mentioned. There is also the recent successful demonstration of manipulating a group of DNA molecules to act as a programmable autonomous computing machine with molecular input, output, software and hardware [15].

Indeed, with all these exciting prospects, there is every indication that Biological Engineering has tremendous work to accomplish in the decades ahead and has ample opportunities to establish itself as a significant engineering discipline and profession in the 21st century.

SUMMARY

The Biological Engineering design process encompasses both 'connecting engineering *to* biology' and 'connecting biology *to* engineering.' For 'connecting engineering to biology,' the object of the design process is a biological system and its design factors are limited by physicochemical principles. Contrastively, for 'connecting biology to engineering,' the object of the design process is a physical system and its design factors are limited by biological attributes. The first case of 'connecting engineering to biology' addresses the design of: (1) *protocol* for biological system; (2) *structure* for biological system; and (3) *model* for biological system. The second case of 'connecting biology to engineering' addresses the design of: (4) *material* based on biological system; (5) *machine/device* based on biological system; and (6) *instrument* based on biological system. Before the implementation of the Biological Engineering design process, it is helpful to identify for each given problem the following parameters: (1) desired task; (2) design object; (3) performance index; (4) design factors; (5) design factors' limitations; and (6) design output.

REFERENCES

1. *Encyclopaedia Britannica*, 15th ed., Encyclopaedia Britannica, Inc., Chicago, IL (1994).
2. J. L. Cuello, *The Descent of Biological Engineering*, Proceedings of the Institute of Biological Engineering, IBE Publications, Athens, GA 3 (2002), pp. 18–30.
3. J. L. Cuello, *An Operational Approach to Systematic Development of a Proposed Framework for Biological Engineering Curriculum*, Proceedings of the Institute of Biological Engineering, IBE Publications, Athens, GA 1 (1998), pp. 54–68.
4. C. Starr, *Biology: Concepts and Applications*, 4th ed., Brooks/Cole-Thomson Learning, Stamford, CT (2000).

5. H. E. Flores, Y. R. Dai, J. L. Cuello, Maldonado-Mendoza and V. M. Loyola-Vargas, Green roots: Photosynthesis and photoautotrophy in an underground plant organ, *Plant Physiology*, **101** (1993), pp. 363–371.
6. W. Lynch, *Implants: Reconstructing the Human Body*, Van Nostrand Reinhold, New York, NY (1982).
7. K. E. Drexler, *Nanosystems: Molecular Machinery, Manufacturing and Computation*, John Wiley & Sons, New York, NY.
8. R. E. Smalley, Of chemistry, love and nanobots, *Scientific American*, **285**(3) (2001), pp. 76–77.
9. S. Nolfi and D. Floreano, *Evolutionary Robotics*, MIT Press, Cambridge, MA (2000).
10. T. Higuchi, T. Niwa, T. Tanaka, H. Iba, H. De Garis and T. Furuya, Evolving hardware with genetic learning: A first step towards building a Darwin machine, in J. A. Meyer, H. L. Roitblat and S. W. Wilson (eds.), *From Animals to Animats 2*, Proceeding of the International Conference on Simulation of Adaptive Behavior, MIT Press, Cambridge, MA (1993).
11. T. Higuchi, M. Iwata, I. Kajitani, H. Iba, H. Hirao, T. Furuya and B. Manderick, Evolvable hardware and its applications to pattern recognition and fault-tolerant systems, in E. Sanchez and M. Tomassini (eds.), *Towards Evolvable Hardware: The Evolutionary Engineering Approach*, Springer Verlag, Berlin (1995), pp. 118–135.
12. H. De Garis, CAM-BRAIN: The evolutionary engineering of a billion neuron artificial brain by 2001 which grows/evolves at electronic speeds inside a cellular automata machine, in E. Sanchez and M. Tomassini (eds.), *Towards Evolvable Hardware: The Evolutionary Engineering Approach*, Springer Verlag, Berlin (1995), pp. 76–98.
13. A. Thompson, Evolving electronic robot controllers that exploit hardware resources, in F. Moran, A. Moreno, J. J. Merelo and P. Chacon (eds.), *Advances in Artificial Life*, Proceedings of the Third European Conference on Artificial Life, Springer Verlag, Berlin (1995).
14. J. B. Pollock, H. Lipson, S. Ficici, P. Funes, G. Hornby and R. A. Watson, Evolutionary techniques in physical robotics, in J. Miller, A. Thompson, P. Thompson and T. C. Fogarty (eds.), *Evolvable Systems: From Biology to Hardware*, Proceedings of the Third International Conference, Springer Verlag, Berlin (1999).
15. Y. Benenson, T. Paz-Elizur, R. Adar, E. Keinan, Z. Livneh and E. Shapiro, Programmable and autonomous computing machine made of biomolecules, *Nature*, **414** (2001), pp. 430–434.

Joel L. Cuello is an Associate Professor in the Department of Agricultural and Biosystems Engineering at the University of Arizona in Tucson, Arizona, USA, where he has been teaching and conducting research since 1995. In 1994, he was a US National Research Council Research Associate at NASA John F. Kennedy Space Center in Cape Canaveral, Florida. He received his Ph.D. and M.Sc. in Agricultural and Biological Engineering from the Pennsylvania State University in 1994 and 1990, respectively, his second M.Sc. in Plant Physiology also from Penn State in 1999, and his B.Sc. in Agricultural Engineering from the University of the Philippines at Los Banos in 1984. His two-pronged research on Biological Engineering and Controlled-Environment Engineering currently includes nano-scale biosensors, chemical production from cell cultures, hydroponic systems and plant lighting systems.