BioSensing and BioActuation
Proposed Research Opportunities/Challenges

1. **Sensor Informatics Guided by Life**
   Understand and emulate data mining and prioritization, as well as decision-making processes, in living organisms to facilitate monitoring, assessment, and control of complex systems in sensor rich environments.

2. **Hierarchical Organization of Biology**
   Determine subtleties underlying the growth of hierarchical bio-structures and bio-systems and their use in sensing/actuation; apply to new multi-scale and multi-functional sensor/actuator concepts.

3. **Spying on Cells: Extracting the Secrets of Cell Function & Response**
   Monitor living cells in-situ and continuously (over multiple time scales) to understand, characterize, and model functional behavior at the molecular and cellular levels; explore biosensor specificity and flexibility for distinct responses to different combinations of stimuli.

4. **Forward Engineering & Design of Biological Components & Systems**
   Synthesize hybrid mechanical/electronic/living systems through system-level integration of biological and engineered components that sense, actuate, compute, regenerate and efficiently allocate resources in order to achieve desired responses and functions.

5. **Multi-scale Bio-digital Hybrid Computing**
   Integrate DNA computers, silicon computers, and biological systems to pioneer networked multi-scale bio-digital hybrid computers.
1. Sensor Informatics Guided by Life

Objectives

• Discover mechanisms of data mining, data prioritization and decision making processes in individual and groups of living organisms.
• Develop new paradigms for the science of information acquisition and processing to facilitate monitoring, assessment, and control of complex systems in sensor rich environments.
• Learn how, what, and why living organisms sense, and how they use information to achieve goals.

Technical Challenges

• Real-time in-vivo monitoring of cellular signal transduction processes amongst organisms.
• Data mining in massively parallel biological systems (e.g. a school of fish).
• Suitably robust stochastic/statistical methods for efficient information analysis and interpretation.
• Adapting decision/control/coordination algorithms, in-network data aggregation and fault-tolerance schemes and sensor-actuator and visualization systems to complex engineered systems.

Impact

• Models of biological communication and information fusion at inter-cellular and complex-system levels.
• Understanding of complex bio-materials and their shapes and surfaces in the context of the system in which they function.
• New paradigms for sensor array design, for prioritization of information during collection and processing and for analysis and decision making in information rich environments.
• Integrated BIO/CISE/ENG/MPS education and research programs.
2. Hierarchical Organization of Biology

**Objectives**

- Identify the principles governing the growth and multifunctional performance of hierarchical biological systems.
- Design multi-functional sensory-actuators and control strategies that take advantage of multi-scale attributes of hierarchical structure observed in biological systems while minimizing energy, materials, and computation requirements.

**Technical Challenges**

- Assessment of nonlinear properties over full range of scales in bio-models.
- Determination of how, what, and why living organisms sense and actuate to achieve specific functional goals.
- Efficient computational models that capture multi-scale hierarchical performance and sensitivity.
- Need for new materials and new design and fabrication methods for coherent integration of different scale structures.

**Impact**

- Comprehension of attributes that regulate formation of hierarchical structures in biological systems.
- New paradigms for sensory-actuator and control system designs.
  - e.g. hierarchical control of systems of subsystems inspired by the organization of the sensorimotor nervous system
- Novel platforms for synergistic multi-scale component integration.
  - e.g. active bridge cables for simultaneous health monitoring, wind load alleviation and fatigue-induced damage mitigation.
- Integrated BIO/CISE/ENG/MPS education and research programs.

---

Hierarchical structure of a tendon used to transmit force from muscle to bone.

3. Spying on Cells: Extracting the Secrets of Cell Function & Response

**Objectives**

- Observe mechanisms of molecular functions in their cellular and intercellular context.
- Detect molecular events *in situ* in the living cell with continuous monitoring to characterize behaviors on multiple time scales.
- Understand complex heterogeneous material structure in the context of function.
- Model the complex and integrated mechanisms of interacting cell functions.

**Technical Challenges**

- Continuous and simultaneous monitoring of multiple cellular events in real time in living cells.
- Design and build instruments and nano-and mems-scale sensors needed for multi-dimensional simultaneous data gathering from within and around living cells.
- Develop techniques to analyze massively parallel data sets.
- Model multiple interacting events in heterogeneous space.

**Impact**

- Understanding mechanisms of cell function at the molecular level and how they are integrated for cell responses.
- New engineering design concepts for sensing in multiple time and length scales.
- Design of cognitive and diagnostic processes based on molecular decision theory models.
- Design of new chemical, physical and biochemical sensing materials based on cell function.
- Integrated cross-disciplinary education and research programs.
4. Forward Engineering and Design of Biological Components and Systems

**Objectives**

- Construct programmed living systems by synthesis and system-level integration of biological and engineered parts.
- Build hybrid mechano/electronic/living systems that sense, actuate, compute, regenerate and efficiently allocate resources for targeted performance objectives.
- Integrate engineering and biological paradigms to develop new chemicals, materials, systems, and computational approaches

**Technical Challenges**

- Design & synthesis of modular programmable parts that perform sensing, actuation and computation in biological systems.
- Modeling of multiple interacting events in heterogeneous space.
- Integration of biological and engineered systems from hybrid components.
- Engineering frameworks for design and construction of complex biological systems
- Modeling and simulation tools that lead to new bio-programming languages

**Impact**

- Increased capacity to manipulate and program biological systems and address major societal challenges (environment, energy, sustainability, health and medicine).
- Development of engineering frameworks (CAD for biology, new programming languages) and general tool sets for building complex biological systems with reliable and robust behavior.
- Integrated cross-disciplinary educational and research programs that address broader issues such as risks and ethics.
5. Multi-scale Biodigital Hybrid Computing

**Objectives**

- Develop multi-scale biodigital hybrid computing paradigm
- Ability to exchange information between biological and electronic systems
- Biophysical and biochemical principles that guide multimolecular interactions
- Understanding molecular function in the context of a multimeric structure
- Methods for assembling complex biomolecular computing networked systems

**Technical Challenges**

- Digitalization of biochemical signals to interface with electronic systems
- Understanding biological computational processes for cooperative and hierarchical communication, computing and control
- Structures of multicomponent functional biological complexes
- New programming models, languages, verification methods for biodigital computer systems
- Error correction and robustness in hybrid biodigital computing systems

**Impact**

- *In vivo* computing for nano-medicine
- New models for cooperative parallel computing methods
- Biodigital computers, integrating DNA computers, silicon computers and biological systems.
- Enable directed nanoscale assembly of circuits
- Nanomachines
- Integrated cross-disciplinary curricula.
Explanation of the figure

Sources of the 5 pictures:
Goodman et al. 2005 Science 310 1661-5
http://alglobus.net/NASAwork/papers/NanoSpace1999/paper.html
http://www.utsa.edu/today/2005/04/apple.cfm
http://www.pha.jhu.edu/~ldb/seminar/fractals.html