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Technical Report

Bio-inspired autonomous engineered systems

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1. Introduction

We live in an era of rapid change, with an evolving concept of engineering at the forefront. This is epitomized by global transformations, not only in the "how and where" of technology development, but also in the pace at which new technologies affect the way we live. There is incredible momentum for further, rapid developments in cognitive engineering and technologies that will penetrate our lives and

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the way we live in unprecedented ways. Crucial to this intense period of development of new technologies will be auto-adaptive media and autonomous engineered systems with five senses information at the broader system-level of multi-complexity. An autonomous system has some key distinctive capabilities, including: **pre-cognition** for prediction; sensors and sensor networks for **recognition** and **detection**; **intelligence** for identification and deduction from massive, incomplete and noisy data, as well as for learning and adaptation; **reaction** for control and regulation; **functional-healing** for recuperation and mitigation; and **energy harvesting** for independence and sustainability. Researchers are investigating various types of new sensors and actuators including those based on chemical reactions. It has been noted that biological organisms possess fast and efficient sensing and actuation means, and that biologically inspired sensing/actuation has become a vigorous research topic in recent years. Such sensors include vision, olfaction, hearing, and touch sensors. Sensor data must be processed and converted to information useful for decision making. This aspect has been studied in recent years, in particular from the viewpoint of sensor networks. One reason for this trend is that microelectromechanical systems (MEMS) technologies have made it possible to mass produce sensors at a significantly reduced unit cost. Another is that there are many engineering problems that are spatially distributed and massively arrayed; sensing is a necessity to monitor or identify their states. Modern computer technologies have made it possible to efficiently organize and sort massive data for decision making. While such technologies have made significant impacts on our daily lives, they rely on the memory size and the computation speed of modern computers and can hardly be regarded as intelligent. Actually, the sheer quantity of data acquired by current and future sensor networks precludes use of traditional centralized data acquisition and analysis. Rather, innovative, dynamic, and adaptive approaches to diagnosis and prognosis must be developed to quickly and robustly extract essential features from the data and identify anomalies necessary for real-time decisions in highly uncertain and evolving environments. This premise applies to both processing of sensor data and decision making. Biological motivations are applicable to research on signal processing and decision making methodologies as well as research on sensors and actuators. Such an example is the natural control mechanisms enabling fish to swim together in schools and birds to fly together in flocks, which motivated researchers to look into coordination or cooperative control of mobile autonomous agents. Bio-inspired autonomous engineering systems (BiAES) introduce bio-inspired considerations in all aspects including sensors/actuators, information processing and intelligent decision making.

To realize such autonomous systems, major R&D efforts are needed to integrate expertise from science and engineering, including design, structures, materials, chemical, biological, mechatronics, sensors and wireless communication, MEMS and NEMS, and system integration and manufacturing.

It is expected that revolutionary advances will be attained by examining the design of systems from the bio-inspired point of view toward one or multiple aspects of sensing and actuation, on-line informatics, and real time decision making/controls. We will refer to resulting systems as bio-inspired autonomous engineered systems.

In the following sections, we will provide detailed descriptions of elements of bio-inspired autonomous engineered systems.

2. Bio-inspired, auto-adaptive media and devices at microscale

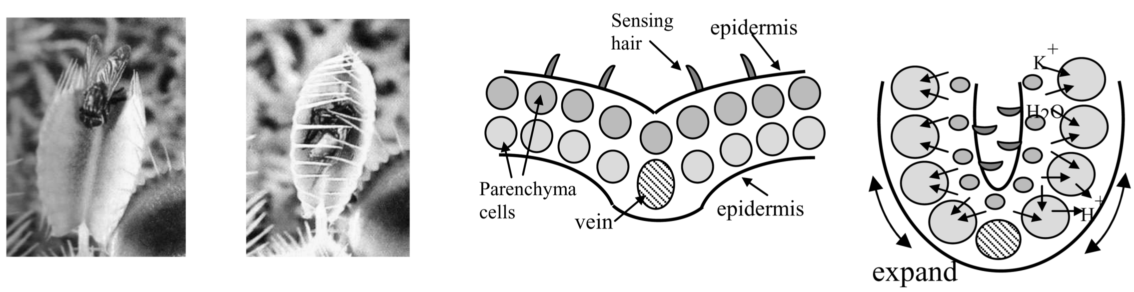
2.1. Current state-of-the-technology

Biological systems are an ideal example of intelligent structural systems with integrated sensing and actuation capability. The knowledge gained from the mechanisms of the biological species is key input for designing intelligent materials and systems. With regard to structural systems, we will be able to learn from energy-conservative actuation mechanisms, and with regard to materials, we will learn from the microstructure-macrobehavior relation of intelligent materials (Taya 2003).

The Venus Fly Trap leaf, Fig. 1, is designed to *sense and* trap flying insects by rapidly closing the leaf-like trap when triggered by sensing antennae located in the center of the leaf. The microscopic mechanism of the Venus Fly Trap leaf is based on controlled ion fluxes creating osmotic movement of water molecules toward the outer-most surface of the leaf, resulting in the expansion of the outer surface and resultant bending. Leaves retain a flat shape as long as the resistance offered by upper and lower epidermis layers is equivalent, and pressure is evenly spread throughout the internal layer. But leaves fold when *the outer epidermal cell layer suddenly expands while the inner does not. This ability to expand rests with the* osmotic pressure created by an ATP-driven proton pump located on the plasma membrane which expels protons, creating both a very negative membrane potential (-120 to -250 mV) and an acidic external pH (Hodick and Sievers 1989, Stahlberg and Van Volkenburgh 1999).

In plants and animals, most epidermal (i.e. skin) cells are capable of sensing mechanical touch, to which they respond with a complex electric signal. When an improved sensing of mechanical touch is essential for the functioning of an organ, the sensitivity is enhanced by surface extrusions in the form of either *sensory hairs* found on the upper side of the leaf pair of the Venus flytrap and the lower part of leaf joints of *Mimosa pudica* or *sensory papillae* found on the surface of tendrils in some *Cucurbita* and *Passiflora* species. Instead of distributing it over many cells, these structures focus the touching force to act on the surface area of only one cell – the sensor cell -- and so amplify the emerging hydraulic pressure.

Autonomic self-healing in rubber trees of the genus Ficus. Natural rubber is a man-made product that derives from colloid latex fluids that occur in different plant species. Hevea brasiliensis trees produce the most copious amounts of latex and are the original source of rubber products. Charles Goodyear heated their sticky latex in the presence of sulfur (vulcanization) and got a moldable liquid that upon cooling lost its stickiness but retained its shape. However, the elasticity of rubber is of little use and consequence for the plants of its origin. Plants developed various types of latex that remain a liquid colloid (white appearance) in the lactifer vessels but are able to polymerize rapidly into a transparent film upon contact with air (which gains access to the latex upon wounding). Mixed with antibiotic and



(a) (b) (c) (d)

Fig. 1 Venus Fly Trap action in catching a flying insect, (a) insect touches the antenna located in the middle of leaf, (b) rapid closure of the leaves trap the insect, (c) cross section view before the leaf motion (d) after the leaf motion

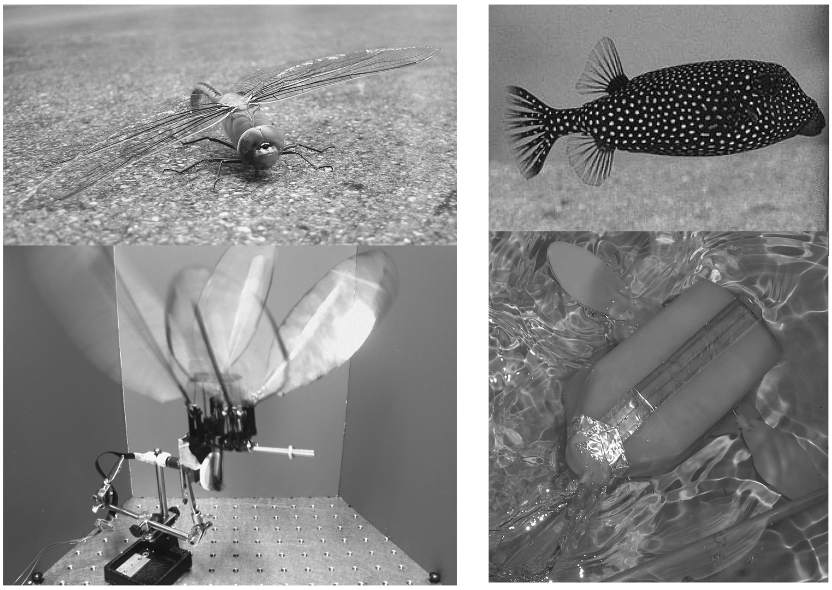


Fig. 2 Bioinspired robot examples: Dragonfly robot on left and boxfish robot on right

antifungal additives, such a substance is an ideal germ-repelling and water-proof cover for surface wounds. The transparency of the cured latex cover makes the presence of a wound as inconspicuous as possible. This self-healing capability of a rubber plant leaf can be easily transferred to human-made self-healing materials, for example, those shown recently in work by White, *et al*. (2001).

Bioinspired robots represent a research topic which has become popular in recent years. Fig. 2 shows such examples.

2.2. What are the knowledge gaps?

The above brief review of sensing and actuation mechanisms, inherent in a few biological species, reveals that there exists a gap between our knowledge based on engineering and the integrated sensing and actuation of biological species. The smaller the gap becomes, the sooner the final goal of achieving the BiAES will be attained. The following is short list of the fundamental knowledge currently missing in the engineering research community that needs to be advanced:

1. Expanding the currently limited list of sensor and actuator materials by bio-inspired design and leveraging the design and processing knowledge of nanotechnology. Such materials are required to be light-weight, energy efficient, cost-effective, hopefully integrable into flexible and wearable structures.
2. Establishing the smooth integration of sensing, cognition and actuation mechanisms, inherent in biology, to a set of new autonomous control algorithms.

The proposed program seeks transformative advances to enhance the five human senses through hybrid composition of bio-inspired sensors and actuators at micro- and nano-scale, both wearable and implantable. Research here will include multi-functional materials/device development as well as integration to engineering systems including the human-machine interface.

3. On-line informatics

On-line informatics provides the framework and backbone for precognition and intelligence to autonomous engineering systems (Spencer, *et al.* 2004).

3.1. Current state-of-the-technology

The capability of dense sensor networks to generate massive amounts of data over short periods of time now exists, to the point where it becomes unwieldy, if not impossible, to bring all data to a central processor; the situation will only be exacerbated in the future. Two approaches are currently in vogue: In the first, processing is decentralized to "smart"[1] sensor nodes and communities, which are required to extract essential features from the data and to identify anomalies. A number of ways to accomplish this task have been proposed, generally requiring real-time comparison between data and predictions of some kind of model in order to assess when action should be taken. In the second, data is compressed at the nodes to the point where it no longer taxes bandwidth and is then sent on for central processing.

Let us divide the technology into two interdependent components, hardware and software. On the hardware side, there have been rapid increases in the capability of "smart" sensors nodes and communities (i.e. embedded systems) due to fast, low power microprocessors. Coincident with this has been the evolution of faster and more efficient wireless standards. With data and information more easily

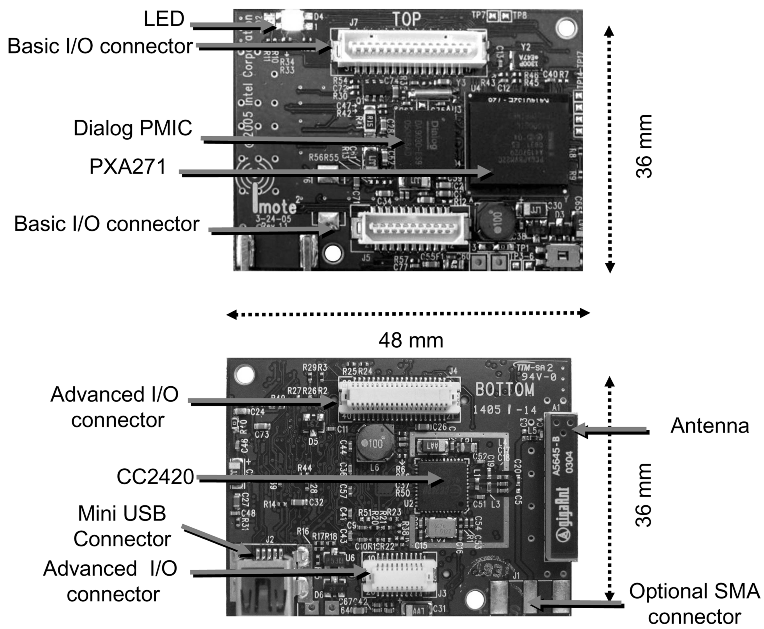


Fig. 3 Intel's Imote[2] smart sensor is one of many new products to come to market

[1]Herein, a "smart" sensor is defined as one with onboard computational and communication capabilities. A group of smart sensors can form a "smart" sensor community. To date, smart sensors have also been wireless.
[2]Smart sensor analyses conducted in 2004 by Frost and Sullivan, Harbor Research, and the Wireless Data Research Group estimate that the size of this market will be between $800M and $1.6B by 2008.

acquired and transported, applications such as smart sensors become exponentially more capable with time. Moreover, the commercial availability of smart sensors hardware (e.g. from Crossbow, Ember, Intel, etc.) has allowed a much broader group of engineers and scientists to develop applications incorporating these sensors (see Fig. 3). On the software side, developments include wireless communication protocols, real-time operating systems, security encryption, and others. Most critical to the current explosion of interest in smart sensor technology[2] have been standardization of the operating system software (e.g. TinyOS) and the wider availability of middleware services.

These, jointly, have enabled the growth of on-line informatics. For example, the emergence of cyberinfrastructures permitting the access to and sharing of large data sets collected from sensors is a relatively recent, important development.

3.2. What are the knowledge gaps?

Multiple strategies to acquire, store, transmit, aggregate, mine, validate, analyze and visualize data are needed in order to make effective and correct decisions. In some cases we must also establish information "trustworthiness" and infer "risk uncertainty," with due consideration of related social sciences, public policy, human behavior. For example, we may need to issue appropriate action and decision making (e.g. control of emergency first-responder deployment) in the wake of disaster, in spite of intentional misinformation (e.g. terrorism) or unintentional misinformation (e.g. errors). Moreover, though the continuous growth in our ability to collect and disseminate data and information is a positive development, we now face the likelihood of data inundation. Tools and technologies which allow for rapid processing and distillation of data in real time must be developed in a scalable and robust manner. Thus, the essential gap between the current state of the art and where we need to be lies in how data is utilized. Currently, analysis is performed in order to mine information from massive amounts of data. Perhaps one should ask, what is the best way to organize, process and visualize data so that users can quickly and decisively react to changes? Can we apply some biological inspiration here? Can nature be emulated and, if so, how? How should local processing and decision-making be integrated? Can we employ warm intelligence among nodes? Fusion? Adaptivity?

Perhaps one can learn by examining how insects function. Most of nature uses information rather than energy to solve problems, whereas man-made systems rely more on energy and less on information. Yet, bugs and other insects have little ability to process information compared with modern computer systems. The likely conclusion is that very simple computing is done at the sensor level, and only a decision or action is sent to the "operator" or brain. Taking this as our paradigm, we need to invent the means to perform local, very simple computing or information processing at the sensor, and broadcast only the minimal amount of information to the central processor. For example, the minimal amount of information may be represented by "features" obtained by a sensor performing pattern recognition. Biological systems perform pattern matching at every level, which allows fast local computation to lead to a hierarchical decision structure.

4. Real time cooperative decision-making

4.1. Current state-of-the-technology

There is a fair bit known in computer science (CS) about distributed decision making (things like

Fig. 4 Fish schooling and car platooning (California PATH)

leader election, consensus, etc). The tools are good, but the problems in CS are "time free"; i.e., the time it takes to make the decision does not really matter. It is rather recent that the cooperative decision making has drawn attention in the control community. A rough outline of technologies would include formation control, distributed optimization, mechanically-inspired approaches, string stability, consensus, and distributed resource allocation.

Formation control has been a popular research topic. Motivations include UAV (Unmanned Air Vehicle) formation control and vehicle platooning for automated highway systems. Vicsek, *et al.* (1995) presented a variety of simulation examples which demonstrate that a nearest neighbor rule may let multiple autonomous points of particles originally heading in different directions eventually move in the same direction despite the absence of centralized coordination. A theoretical explanation for this behavior was provided by Jadbabaie, Lin and Morse (2005). This work was an outcome of an NSF KDI (Knowledge and Distributed Intelligence) initiative award, "Coordinated Motion of Natural and Man-Made Groups" (1999-2004, PI: A. S. Morse). This research had clearly biological motivations. On the KDI webpage, Jadbabaie is quoted, "We were trying to find mathematical proofs of under what conditions these types of coordination are possible. We started analyzing some mathematical models that have some biological motivations—a simple model of how birds would fly in a group, flock together." When the task becomes more complicated, neighboring rules alone may not be sufficient to attain control objectives. A good example is vehicle platooning for automated highway systems. A vehicle platoon is a string of vehicles moving in one dimension so that they all follow a lead vehicle with a constant spacing between successive vehicles. Vehicle platooning is a counter part in the engineering world of fish schooling in the biological world (see Fig. 4). In automated driving, the controller on board each vehicle determines the acceleration/deceleration command so that the spacing between the vehicle and the preceding vehicle is maintained at the desired value. It has been shown that if the control law is based on a local feedback control law (i.e. the control input depends on the spacing error relative to the preceding vehicle), spacing error amplification takes place in the vehicle string. The error amplification problem can be avoided if the position, velocity and acceleration of the lead vehicle are shared by all vehicles in the platoon. Note that, in the vehicle string example, the control decision is still decentralized at each vehicle though the feedback information is not limited to nearby vehicles. If the control decisions for all actuators are made by one decision making logic based on information gathered from all agents or members in the group, we have a centralized system. Traditional multi-variable control theories provide the scientific basis for centralized systems. The centralized approach is often impractical when many agents are involved, and this point motivated bio-inspired decision making logics.

4.2. What are the knowledge gaps?

The Vicsek model indicates that a decision based on nearby information may be sufficient for achieving simple objectives such as letting all agents point the same direction. In the vehicle platoon problem, nearby information was not sufficient to avoid the amplification of spacing error among vehicles. In cooperative decision making, it is critically important to understand how the data or information from a set of distributed sensors or agents should be shared to achieve objectives. The problem becomes even more complicated if feedback control based on sensor data is involved. There are a number of questions which must be answered: For example, how does communication topology influence convergence, region of attraction, robustness? What about cooperative decision-making that is multi-scale? What if the collective is heterogeneous? What can we say about the global dynamics in cooperative decision-making systems? What can we learn from what cooperative decision-making collectives do in nature? How do we relate analytic results to reasonable biological models to help uncover mechanisms that link individual behavior to group behavior? New protocols, algorithms, and objectives must be developed incorporating adaptation and self-organization to achieve self-recovery and fault tolerance to further ensure reliability of the machine and built environment and safety of humans.

Sensor networks are a really compelling setting for cooperative decision-making. Yet, it is enormously challenging to determine strategies for cooperative decision making and control that maximize the utility of the sensor network. This is true particularly when the sampled environment is time varying and multi-scale, when the network is mobile, heterogeneous, and susceptible to disturbances, and so on.

It should be noted that methodology-driven research has been a cause of knowledge gaps. Namely, the knowledge gaps are pushing the various fields into domains for which there were not designed. This means that one may be using an auction-based mechanism designed for optimal behavior in equilibrium in off-equilibrium. It may mean using a reinforcement-learner in areas where the sampling of the action space is inadequate. It may mean using physics-based algorithm when the "particles" aren't following the rules of nature. It may mean using adaptive control algorithms when the system/ plant models are woefully inadequate. In all of those, the gaps are to find how to mix these strategies and determine how far one can push them before they "break".

The formation control problem and the vehicle string problem are good examples of cooperative decision making problems where researchers succeeded in finding new principles that make respective multi-agent, systems function. It is expected that such transformative ideas keep generated from real, i.e. not artificial, multi-agent problems. In this sense, pertinent examples are a key element in successful endeavors to find new principles for cooperative decision making.

5. Some examples of bio-inspired autonomous engineered systems

As stated in the Introduction, bio-inspired autonomous engineered systems are featured with bio-inspired points of view at one or multiple aspects of sensing and actuation, processing/conversion of sensor data to knowledge and decision making. In the previous sections, descriptions of elements of bio-inspired autonomous engineered systems were given. In this section, we will give a few examples of bio-inspired autonomous engineered systems.

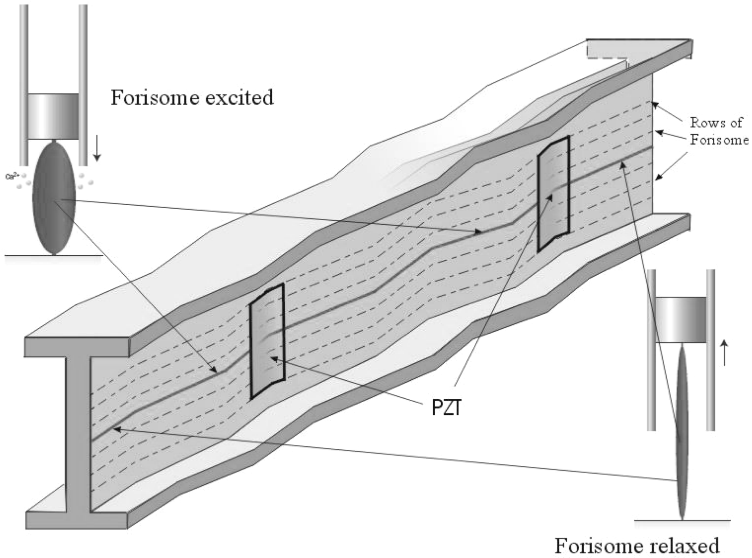


Fig. 5 Conceptual sensory nerve system for civil structures employing forisomes as the mechanoreceptors, nerve fibers, and spinocervical tract to the nodal and central processing units

5.1. Nervous system for control, monitoring, and diagnostics of civil structures

Globally, civil infrastructure is deteriorating at an alarming rate caused by overuse, overloading, aging, damage or failure due to natural or man-made hazards. With such a vast network of deteriorating infrastructure, there is a growing interest in continuous monitoring technologies. Future civil structures will be equipped with a Structural Nervous System that mimics key attributes of a human nervous system providing a truly distributed sensor and control system. This nervous system is made up of building blocks that are designed based on mechanoreceptors as a fundamentally new approach for the development of a structural health monitoring and diagnostic system that utilizes the plant-protein forisomes, a novel non-living biological material capable of sensing and actuation (see Fig. 5). Structural health monitoring (SHM) has been an active research area in aerospace, civil and mechanical engineering for some time. BiAES will bring transformative changes to the important area of SHM.

5.2. Security and safety of public space

We may find in the customs area of a future airport a group of robots equipped with olfactory sensors. With a help of vision cameras to cover the entire customs area, the robot group never misses a suspect carrying explosives, drugs, as well as dangerous chemicals. This is only one of many scenarios that demonstrate the advantages of bio-inspired sensors and advanced on-line informatics. BiAES will be a key technology element to ensure the security and safety of public spaces.

5.3. BIAES applications to human-machine interface

Transformative advances here will provide mini/micro devices, robots, and machines with the ability to anticipate human needs and intentions in the absence of explicit instructions, develop connective "tissue" such as artificial muscle, and enable seamless energy and information exchange through the interface. Wearable jackets may monitor body temperature, heart beat pulse, cholesterol level, sugar level, again using the body temperature as the energy source to run the electric power by using thermoelectrics.

6. What is most needed to fill the identified gaps and to make significant advances?

We have reviewed the current state-of-the-technology and the knowledge gaps in bio-inspired, auto-adaptive media and devices at microscale, on-line informatics, and cooperative decision-making. In filling the identified gaps, multi-disciplinary team efforts and cooperation are necessary. Broad representations from material science, biology, mathematics, computer science and application domains will be required. Furthermore, from the view point of bio-inspired autonomous "systems", clear compelling and challenging applications will be necessary. We are going to evolve new approaches and frameworks by solving some specific problems and then taking a step back and formalizing the path to the solution.

Broader impacts of research on BiAES will be extensive and include enhanced quality of life and a more secure and safer society. NSF recently established a new engineering research center (ERC), Quality of Life Technology Engineering Research Center (QoLT ERC), focusing on improving Americans' quality of life at Carnegie Mellon University (http://www.ri.cmu.edu/projects/project_583.html).

Currently there are no formal educational or research programs (at least in the United States) that can prepare the next generation workforce for this emerging area of bio-inspired autonomous engineered systems. In some cases, research programs have been organized as less formal cross-institute collaborative research groupings. However, many subjects critical to bio-inspired autonomous engineered systems are challenging parts of the materials science discipline, the information technology and computer science disciplines as well as the decision making and control disciplines. We need to bring together the inter-related disciplines of mathematics, software, computing, system architecture, communication, and electronics in an innovative and forward-looking structure. In such a dynamic and rapidly changing environment, we need to respond rapidly to the needs of students, industry, and society.

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