The Interplay of Biology and Engineering for Smarter Applications

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I would like to express my gratitude to the conference's organizing committee for inviting me here, and allowing to me to share some thoughts with you today on what is a very hot topic in agriculture, in biological engineering, and in almost every field and application that is touched by sensors. These are very exciting times, indeed.

Given that this year commemorates 100 years of agricultural and biological (whether or not it has always been explicated stated) engineering as a professional society, it is worth examining that legacy briefly. This conference's organizers have done that in their theme statement. Agricultural mechanization has indeed been a great achievement. It has brought relative food security to millions of people, in this country and globally, and has generated great prosperity for several generations of rural Americans—not just farmers, but the companion enterprises that provide financial resources, transportation, and retail goods and services. It helped generate a culture and way of life that was both celebrated and scrutinized in artistic and literary depictions over the years—Garrison Keillor's *A Prairie Home Companion*, Steinbeck's *Grapes of Wrath*, Rachel Carson's *Silent Spring* (incidentally, this year is also the 100th anniversary of her birth), Aldo Leopold's *Sand County Almanac*, Woody Guthrie's music, *Wizard of Oz*, and Grant Wood's *American Gothic*, to mention only a few. The reach of this boon in agricultural productivity—driven partly by mechanization—extends far beyond agriculture and food production.

Because mechanization was part of the Industrial Revolution, it carried with it many of those same attitudes of production maximization, resource exploitation, short-term horizons, and economies of scale (bigger-is-better) that typified the late 19th and early 20th centuries. This industrialization of agriculture led to, as we have now come to realize, degraded soil, air, and water resources, high-input (including energy) and expensive farming practices, loss of rural communities and their character, and food production and distribution systems that have little redundancy and resiliency. I mention these things—not to be a Negative Nellie or to dampen the celebration of this very noteworthy 100-year anniversary—but, rather to point out that we have learned much in the past century about the biophysical and social constraints of agriculture and natural resources and of food production. Accepting those past failings and subsequent realizations, alongside agriculture's successes, should then guide us in our new endeavors forward—particularly in the area of biological sensorics, where we have new technologies and applications that can make a difference in how we produce and distribution food, feed, and fiber and in how we treat our partnership with the land (including air, soil, and water).

Sensors: Then, Now, and Later

To say that sensors have invaded every aspect of our lives is probably stating the tacitly obvious, given this conference and its audience. Yet, I think that it's worth reflecting briefly on how the sensor-izing of society has changed human lives in only the relatively recent past.

Prior to 1840, there was no such thing as weather forecasting, unless someone made weather observations, hopped on a train, and traveled to a downwind location where they could then amaze everyone with their predictive prowess. Weather just happened, and that was that. Once the telegraph was available, however, weather observations could be made at multiple locations, communicated to a central location, and used to develop patterns of air mass movement and their characteristics. Since that time, we have come to use temperature, humidity, infrared, radar, and a variety of ground-based and airborne sensors to measure atmospheric conditions at thousands of location around the globe. Daily and hourly forecasts have become extremely accurate and very location specific. Handheld devices, such as cell phones, can even provide up-to-the-minute forecasts and imagery (e.g., radar image loops) for any location we choose. Daily activities can be coordinated with reliably anticipated weather events, and we can avoid unpleasant or potentially dangerous situations.

Much more recently, we have the introduction of sensors, and now sensor systems, into the family automobile. The weighted average number of sensors in the typical North American light vehicle almost doubled during the 1990's, rising from 18 in 1992 to 30 in 2002. With recent requirements for electronic stability control systems and continued sophistication of internal combustion technology, it is likely that in the upcoming 2008 model year that number may have already doubled again. Various accident avoidance systems nearing commercialization will quickly push that number much higher. Routinely now, automobile occupants are able to walk away from high-speed collisions, whereas two decades ago everyone would have been killed most of the time. Not to be outdone by passing vehicles, in many metropolitan areas, municipalities issue thousands of traffic tickets annually through the mail, based on camera-detected red-light violations and unmanned radar-detected speed violations.

Closer to home, washing machines and clothes driers automatically adjust water levels or drying times based on sensing of the wash load. While not yet widespread, refrigerators are available that can monitor food age/spoilage and alert the owner (and even create a grocery list for replacement products). Currently, sensor diffusion is occurring in larger, more expensive machines and devices (i.e., automobiles, large appliances) because of the efficiency improvements they can achieve in those more complex devices, and due to the relatively small marginal cost for deployment in those expensive items. As sensor costs and size continue to decline, it makes sense that they will increasingly be found in smaller and less expensive devices.

In a more futuristic vein, a small-scale social science study of human-robot interactions was published recently that examined how people's behavior changed over the course of a year using the Roomba[1] robotic vacuum cleaner. They found some surprising behavior changes, in addition to "adoptive" naming of their new cleaning partners. Cleaning roles changed with more men and younger members of the families participating, often working in pairs. Traditional planned

[1] Trade names are used for informational purposes only. No endorsement by the U.S. Dept. of Agriculture is implied.

cleaning times were abandoned for an opportunistic approach. Younger people found themselves cleaning more frequently. The robotic vacuum even changed lifestyles, with some deciding that having an automated vacuum that could clean underneath furniture was worth the extra effort to keep clutter off the floors. Obviously, these are not dramatic life-changing events, but they point to the relative ease with which we adapt to new technologies and incorporate them into our lives, for better or worse.

Furthermore, expectations are that the future will be similar to the present with regard to sensor deployment, only more so. In a 2006 survey of Institute for Electrical and Electronics Engineers (IEEE) Fellows by the Institute for the Future, "sensory-rich information environments" was one of the five most common predictions for the next 50 years. A few of the specific predictions that survey respondents were queried about appear in Table 1. From the data, it appears that these scientists expect that many of the technologies currently under development will eventually become deployed. However, their appearance in our lives may be one to two decades away yet in many cases. The only technologies forecast as *unlikely* by a high percentage of respondents are eldercare robots and self-driving cars. In those two cases, the hurdles may be more legal, social, and psychological than limitations in science and technology advances. One can see glimpses of the future in products and technologies all around us. As novelist William Gibson once observed, "The future's already arrived; it's just not evenly distributed yet."

"Smart" Applications

For the purposes of this discussion, let's adopt the following definition of a "smart application." An application of sensors is termed *smart* if, in addition to making its intended measurements, the sensor (and its companion hardware or software environment) can formulate an interpretation of those data in way that has been customarily performed by humans. This interpretation activity includes several tasks after signal transduction and digitization (in order of complexity): analysis and description, situation assessment, and course of action, where each relies on the preceding task. These tasks reflect successively higher levels of processing—and concomitant data reduction—until we eventually arrive at a go/no-go or 1-of-N decision. However, while a home furnace thermostat can take a "course of action" by turning the furnace *on* when the temperature drops to a certain level (and turning *off* the furnace when the temperature rises to a set threshold), it does not perform any intervening interpretation tasks that demonstrate a sequence of low- to high-level information processing that we typically associate with intelligence. The actual end-point function of a smart application is not important (e.g., whether it's diagnosis or control), rather it's the processing of data-rich sensory input through to knowledge-rich decision making that defines "smartness." The thermostat and similar sensor applications, therefore, are not "smart" in the sense described here.

Of course there are also "dumb" smart applications. Smart applications that are robust, and perform well, with regard to missing or contradictory data, to unfamiliar situations, or to partial system faults, we would consider truly smart. Typically, such applications also have some redundancy built into them to afford some measure of resiliency. Smart applications without those features, we often call "smart," but really consider them to be merely "sophisticated" because they don't respond in *reasonable* ways (in the human sense) when confronted with situations outside of the comfortable norm.

Table 1. Selected questions and responses from a survey of IEEE Fellows conducted by the Institute for the Future, looking at technology adoption in the next 50 years.

Futures Question	Likelihood?[a]		When is this likely to occur?[b]	
Will "smart dust" devices become widely deployed in sensor networks?	Unlikely	15.1	10 years or less	29
	Likely	51.9	11 to 20 years	40.3
Will printed bar codes be replaced by smart-tag technologies, e.g., RFID?	Unlikely	2.3	10 years or less	63.1
	Equal chance	8.5	11 to 20 years	30.1
	Likely	86.8		
Will sensor networks that scavenge power be widely used?	Unlikely	7.7	10 years or less	38.3
	Equal chance	22.5	11 to 20 years	44.4
	Likely	66.2		
Will microelectromechanical systems be widely applied in medicine?	Unlikely	15.4	10 years or less	19.6
	Equal chance	22.1	11 to 20 years	50
	Likely	59.6		
Will nanoelectromechanical systems go commercial?	Unlikely	11.5	10 years or less	27.6
	Equal chance	26.9	11 to 20 years	55.2
	Likely	57.7		
Will scientists have accurate computational models of the human senses?	Unlikely	13.4		
	Equal chance	30.5	N/A	
	Likely	53.7		
Will microscale robotics become viable?	Unlikely	15.4	10 years or less	9.6
	Equal chance	26.9	11 to 20 years	53.8
	Likely	52.9		
Will household robotics be widely adopted?	Unlikely	17.8	10 years or less	16.1
	Equal chance	29.5	11 to 20 years	50
	Likely	48.8		
Will humanoid robots care for the elderly in their homes?	Unlikely	39.5		
	Equal chance	27.9	N/A	
	Likely	27.1		
Will self-driving cars be in commercial production?	Unlikely	39.5		
	Equal chance	30.2	N/A	
	Likely	26.4		

[a] Percentage of respondents; not all respondents answered all questions. Shading indicates those forecasts deemed likely by at least 50% of respondents.
[b] Percentage of respondents. If a respondent felt that a forecast had a 60% chance of occurring, they were asked to specify a time frame. Time frames are omitted for those forecasts that are very uncertain or when the number of respondents is small.

Why is this important? As sensors and sensor systems become ever more pervasive, we are coming to rely on them more and more. However, more sensors, showing us more data, are not, in and of themselves, all that helpful. Our growing reliance on sensor devices means that we are no longer just expecting (or needing) sensors to collect data, but demand that they do something more with those data. That "something more" often means performing some "human-like" tasks in our stead, which might be controlling a vehicle on a slippery road or cooking a microware dinner just right. In an increasingly data-rich and complex world in which human time and attention become more compressed with each passing decade, smart applications and devices may be our only sanity saviors—short of abandoning everything and moving into a one-room shack in the woods. Pushing for smarter applications results in engineered systems that are safer, more efficient (in terms of time, money, or resources), or that perform better than previous systems or than people. When one considers the technical skill and sophistication of the average person—e.g., most people never successfully programmed their VCRs in the 1990's—it becomes readily apparent that we need all the smart applications that we can develop and deploy.

Biology Influencing Engineering

The idea of "interplay" as expressed in the title of this talk suggests that there is a two-way flow of *information* and *ideas* between biological systems and engineered systems. Most of this talk will consider a flow of *information* principally, such that engineered components monitor, adapt, and control biological forms, functions, and process. That is our most common interpretation of biological engineering, in general, and biological sensorics in particular. However, if we only think of the biological systems in agriculture and natural resources as data sources that are subject to manipulation, we may miss out on some valuable opportunities. Biological systems have evolved over the course of millions of years, and so have optimized most of their forms, functions, and processes to be both effective and efficient. There is much that can be learned and borrowed from biological systems and applied to our man-made systems.

Biomimetics (biology as prototype)

Biomimetics (or more generally *bionics*) refers to the flow of ideas from biology to engineering. In biomimetics, engineers develop synthetic methods based upon biological systems and their characteristic forms, functions, and processes. Of course, this concept is very old, indeed, as even the earliest attempts at human flight tried to mimic exactly the biological form and function found in bird species—without much success, however. Many of the best known examples of biomimetic successes, however, have borrowed biological forms (structures) less literally than those early flight attempts. These include the electronic nose (as a copy of human olfaction), Velcro (as a copy of plant burrs), dirt- and water-repellant paints (as copies of the lotus flower surface), and ultrasound imaging (as a parody of echolocation by bats). For the most part, these applications have viewed biology as *prototype*, and sought to duplicate, or improve upon, its natural forms in creating new man-made products.

Biopedagogics (biology as teacher)

Biological systems, however, also contain many important processes that can serve as biological models for engineering solutions. In this sense, biomimetics becomes a creativity technique that borrows *ideas* from biological functions and process. Here, biology is more akin to *teacher*, rather than prototype, and the biological influence could be termed *biopedagogics*. Examples of biopedagogics include: artificial neural networks, genetic algorithms, and swarm intelligence; which, while computer science techniques, have been borrowed by many biological engineers for solving problems in machine vision, sorting/classification, and optimization. Recently, group decision making in bee populations—in particular, hive relocation—has been shown to be equivalent to "range voting," which, quite possibly, might have applications in sensor network communication and problem solving. It is estimated by Julian Vincent, professor of biomimetics at the University of Bath in the UK, that there is only a 10% overlap between biology and technology in terms of the mechanisms used. So there is still ample opportunity to learn more from the engineering that biology has developed and tested over the millennia. If you are an engineer, or even a quasi-engineer (like myself), you can't help but see these biological models in the natural world, if you just make yourself available to them.

Cyborg Bionics (biology as engineered component)

In a recently emerging area, where the interplay of biology and engineering is even more intimately connected, we are seeing hybrid systems that are part organism and part machine. In principle, some aspects of a device or system are better handled by biology, and other components perform better when engineered. By merging capabilities from each world, the best parts of each toolkit can be employed to create a superior device than would otherwise occur from either option alone. One of the most notable examples of this hybridization is biosensors. Here, the sensing element is coated with biological receptors (e.g., antibodies, DNA) that capture specific antigens or proteins, which in turn alter the underlying material's electrical or mechanical properties, creating a detectable signal. In other cases, biology can serve as a power source. For example, devices that are imbedded within, or in very close proximity to, biological organisms, can scavenge heat or movement to generate small amounts of electrical power. In addition to the use of biology as sensing elements or power sources, it may also be useful in some applications to let biology serve as an analog output. So, instead of digitizing, and communicating a sensed signal via engineering, these functions could be achieved by chemically or electrically transmitting directly to a host, or coupled, organism, which would then display the appropriate output signal. Merging biology and engineering at the level of cyborg bionics is still in its infancy, and has many hurdles to overcome, in practice. However, even without successfully deployed applications, there is much new science being developed, and some of those discoveries could also be applied in the biomimetic and biopedagogic areas noted previously.

Emphasis Areas

Returning again to the *information flow* perspective of biological sensorics, I would like to devote the remainder of this talk to several important emphasis areas. For lack of any better terminology, *emphasis* areas here include some of those topics that: (1) deserve, or will require, attention in the coming decade, (2) are poised to greatly improve management of agricultural, food, and natural systems, or (3) should partially dictate how engineering science and technology progresses. The topics covered here are not intended to be exhaustive, nor the only important ones. We will hear about much interesting work in the next day and one-half; just because some of those efforts do not fall into one of the topics I've chosen to highlight does not diminish their significance in any way. These emphasis areas fall into three broad categories: technology, applications, and companion issues.

Technologies

Many different technologies could be highlighted here, but I chose two that are closely linked. The first, *embedded sensors and sensor networks* will become important for lots of different applications in agriculture, food, and natural resources. The trend toward smaller size and lower cost mean that sensors will change from being part of stand-alone instruments to becoming part of how we produce food, feed, and fiber and how we manage natural resources.

The second, *information technology* (including hardware, software, and telecommunications), will make the first one (embedded sensors and sensor networks) meaningful. As sensors are deployed in large quantities, the ability to communicate, store, search, validate, interpret, and model those data and to inform decision making will be crucial to adoption and to eventually realizing benefits.

Embedded Sensors and Sensor Networks

Sensors are becoming solutions rather than devices. Common characteristics of sensing systems include integration of multiple sensors, multiple system concepts/approaches, autonomous operation, flexibility, onboard intelligence, and the growing use of wireless interfaces. This makes them ideally suited to a wide variety of agricultural and forestry applications wherein wide-area coverage and/or frequent measurement are important. Features of agriculture settings that complicate applications, however, are remoteness (creating communication and power problems), dirty and continually changing environments, and an unconstrained natural world.

One of the research areas where embedded sensors will have growing importance is for new *mechatronic* systems, e.g. robotic or automated machinery. For example, marginal changes to machinery and equipment that involve motion and position/attitude sensors and vision systems to monitor the human-machine environment and control systems to warn operators or mitigate hazardous situations could dramatically improve worker safety. In the case of more sophisticated technologies, machinery/equipment can be developed to act as extensions of the human operator by augmenting worker capabilities. This would allow workers to improve their performance (speed and/or skill)—resulting in efficiencies and product quality increases—and limit their exposure to the most hazardous parts of their jobs, thereby improving overall safety. At the far end of the spectrum are fully autonomous machines, or squads of machines, that perform tasks with little, or no, operator intervention. In fact, it may be the case that a single operator would monitor a small army of worker robots from a centralized, remote location—somewhat like an air-traffic controller. Extensive use of robotic workers will likely require substantial changes in crop growth habits/parameters, timing/frequency/extent of culturing activities, and pre- and post-harvest product handling. Applications of such mechatronic systems to production in the specialty crop industries are discussed later.

Advances in automation, robotics, and sensors will require multidisciplinary efforts across a wide range of scientific disciplines and, in aggregate, should include the following characteristics:

- Investigators from the biological sciences on the production side will need to work in concert with engineers from materials science, computer science, and electrical and mechanical engineering to produce solutions well-matched to the chosen application area.
- While focused application development efforts may be narrow in scope, the developed technologies will also be applicable to many other agricultural production environments.
- Vision systems, robotic manipulation, sensing technologies, power systems, locomotive mechanisms, communication systems, and intelligent, fault-tolerant

control systems constitute the important subsystems that will need individual development, as well as, eventual systems integration.

- In addition to research and development efforts to create new mechatronic systems, there is also an urgent need to train a new cohort of agricultural and biological engineers in the systems comprising these new technologies. Without an infusion of properly trained professionals, commercialization of newly developed technologies will falter.

Aside from deployment on mechatronic systems, future sensor networks will invade the biological environment and "cohabitate" with plants and animals. If the systems are to be deployed in remote environments—uninhabited forest lands or infrequently visited fields, for example—the networks themselves must be self-configuring and power self-sufficient. With deployment in the thousands, hand-configuration is simply not practical. Techniques are being considered that "virally" configure and program each sensor with new software, injecting new code into the network and letting it proliferate from sensor to sensor. Additionally, the architectures of these future sensing networks are quite different than familiar network architectures like that of the Internet. The real world is noisy and unpredictable. The overall network will need to be fault tolerant, allowing for loss of various sensor motes from time to time. Tight power constraints may require that the sensor's radio is almost always off, switching on only to transmit or receive data in short bursts. This means that power scavenging and efficiency will be critical operational parameters, as will on-board data synthesis and compression. Finally, determining optimal physical locations becomes an important open issue—where must sensors be placed to accurately and reliably measure what is requested? There may very well be biological models that could help us solve that problem.

<u>Information Technology</u>

A common thread running through these, and all other developments in ubiquitous sensing, is the vast amounts of data generated, and a need to have the ubiquitous sensor networks process this data in order to return decisions and information. Sensor networks become a dynamic organism far more powerful and user-friendly than the traditional view of a sensor as a widget, an individual component that needs to be deployed, programmed, and interrogated. The metaphysical view of sensor networks as organism-like in their behavior and characteristics further emphasize the interplay of biology and engineering.

In terms of the embedded systems mentioned previously, we can distinguish two separate types of data and their characteristics. In the case of mechatronic systems, data are used real-time and collected almost continually. Data storage needs are almost non-existent, but high-throughput data processing and high-level decision making are crucial. Vision systems and hazard/people avoidance behaviors require complex interpretation of large volumes of data each and every second. Additionally, there will be operational sensors for measuring yield or guiding a picking arm or spray nozzle. Some of those operations will require data storage and perhaps communication with a central controller to download tactical instructions for the machine.

In the second case, plant-level sensors may continuously monitor field or forest conditions. These data could be used to detect pest or disease conditions, to inform plant development, or other biological or economic, models (in concert with hourly weather data), or to alert for water or nutrient needs. Data storage and transmission needs could be extensive in these instances—depending on geographic coverage and frequency of collection—or could rely on spatial aggregation across a sub-network to communicate averages rather than many individual measurements. Depending on the need to warehouse extensive high-density and high-frequency data collection, preliminary data processing could occur on sensor motes or on the network to make field-based decisions and take action (e.g., opening an irrigation valve). These needs for information processing will open up many research opportunties regarding mote vs. network processing (local or distributed) and how decision are made (a single set of decision rules or some bee-like, range voting process).

Applications

As with the technology area, there are many different applications (or application areas) that could be highlighted. The two that follow were selected because of their growing importance to our national food system.

Specialty Crops

The Specialty Crop Competitiveness Act of 2004 (P.L. 108-465) defines "specialty crops" as fruits and vegetables, tree nuts, dried fruits, and nursery crops (including floriculture and greenhouse operations, and installation and maintenance industries). One of the findings of that Act is that "a secure domestic food supply is a national security imperative for the United States." Furthermore, three out of five components of USDA's food pyramid include specialty crop foods, so they represent a critical portion of the recommended nutritional program for U.S. citizens. Without a strong and viable specialty crop industry in the United States, a significant portion of our nation's nutritional base would be reliant exclusively on foreign markets. This puts readily available and affordable health-conscious foods at risk for U.S. citizenry. Specialty crop producers and processors are major contributors to the U.S. agriculture economy. The total value of U.S. specialty crops ($49 billion in sales) now exceeds the combined value of the five major program crops ($45.8 billion in sales). There is much at stake for food security, rural economies, and balance of trade that could benefit from healthy and productive specialty crop industries.

One of the biggest economic problems that the specialty crop industries face is related to labor. This includes labor availability, cost, and skill. For many growers, labor expenses amount to 40-60% of production costs. In most cases, foreign growers can produce, package, and transport fruits and vegetables for sale in the U.S. at less cost than domestic producers, owing to dramatically lower labor costs abroad. Many U.S. producers have reached a crucial point where high labor costs, limited access to international markets, and increased competition from abroad could eliminate many specialty crop industries within the next 10 years. As they have for decades, most of these industries still rely extensively on low-wage, seasonal, unskilled labor. Yet, seasonal low-wage jobs can provide only marginal economic support for rural retail and commercial businesses. A permanent, highly skilled labor force—along with more efficient production technologies—creates community stability and a sound economic base for public services and secondary industries.

Different segments of the specialty crop industry (e.g., wine/grape, citrus, apple, stone fruits, ornamentals, etc.) have been organizing independently during the past several years to address critical research needs. However, because each segment, individually, only represents a relatively small portion of the overall specialty crop industry, many of their needs do not receive attention in national research programs. Consequently, those individual industry segments have created a research collective to examine common research needs across many different specialty crops. What they found is that they have much in common. One of their primary industry-wide concerns is the availability of, and cost of, labor—their single greatest production cost—that places them in an untenable competitive position in the global marketplace. But, that is only part of the story. These industries also need tools and technologies that can improve production efficiency, product quality, post-harvest operations, and reduce their environmental footprint. They have agreed that automation, robotics, precision agriculture, sensors, and other advanced technologies are needed to help their industries and its producers become more efficient, productive, and sustainable.

While other national efforts are underway to develop biological/horticultural solutions to some of these problems, there have been loud and persistent calls from stakeholders for *engineering science and technology* approaches. On April 24-25, 2007, a workshop convened in Arlington VA to examine those needs across several specialty crop industries. Workshop attendees also discussed current and future engineering capabilities and how those might be brought to bear on the problems faced by producers and processors. Attendees included program managers from a variety of federal agencies: NASA, NSF, NIOSH, CSREES, ARS, NIST, and AMS; producers and representative from five specialty crop industries: tree fruit & nuts, citrus, wine & grape, berries & brambles, and ornamentals; and researchers, educators, and outreach specialists from both public and private institutions. To ensure that workshop discussion and outcomes were well grounded and incorporated biological and human dimensions, there was also participation from biological and social science disciplines. In some cases, technologies already exist that can be applied to production and processing problems. For other problems, the engineering science base needs to be expanded to ensure that technologies will be available in the years ahead. A brief summary of some of the findings from that workshop are presented here.

The following two tables (Table 2, **Error! Reference source not found.**) illustrate some of the need areas identified by specialty crop industries during the recent workshop. Cultural practices, product quality, and water and pest management are common themes across these industries. Other specialty crop industries represented at the workshop expressed similar concerns. While engineering capacity currently exists in some of those defined need areas, little is now directed toward applications for those industries. Whereas in the mechanization of cultural practices, there exists a significant R&D gap.

Of particular interest to this conference are the R&D directions that the workshop identified in the area of sensor and sensor networks (Table 4). In looking at their wish list of sensors, there is considerable work that remains to be done. Sensor development, of course, is only part of that effort, the information handling and application components must be developed in concert with the sensing hardware.

Product Traceability

Traceability in the food products industry can mean many different things and have many potential benefits, depending on what one includes in the concept. In its March 2002 study entitled Traceability in the Food Chain, the European Food Standards Agency examined the role of traceability systems in both food safety and consumer interest. The report found:

- Consumers gain mostly hidden benefits from traceability (*i.e.*, more effective achievement of food safety and an increased effectiveness of recall in emergencies).

- Traceability also has a role to play in promotion of informed consumer choice because it offers the potential to verify label information on product and ingredient history.

Table 2. Engineering needs identified by the wine and grape industry.

Issue/need/concern	Priority[a]	Urgency[b]
Mechanization of cultural practices (e.g., pruning, thinning, canopy mgmt, harvesting)	3	0-3+
Water management	3	3-6, 6+
Waste stream management	3	3-6, 6+
Energy use/capture/renewal	3	3-6, 6+
Food safety (including traceability, sanitation, data mgmt)	3	0-3
Pest management & application technology (e.g., spraying, weeds, environmental and human safety, nutrient mgmt)	2	0-3+
Crop development forecasting (e.g., yield, maturation, quality)	2	3-6, 6+
Site selection & assessment	2	3-6, 6+
Soil chemistry, physics, and dust mgmt	2	0-3, 3-6

[a] High (3) to low (1). For brevity, those with low priority are not listed here.
[b] Years: near term (0-3), medium term (3-6), long term (6+)

Table 3. Engineering needs identified by the citrus industry.

Issue/need/concern	Priority[a]	Urgency[b]
Pest/disease detection & management	3	0-3
Product quality & product harvesting	3	3-6, 6+
Pest management & application technology (e.g., spraying insecticides/herbicides/fungicides)	2	0-3
Water management & utilization	2	6+
System approach to production (including plant, environment, and business economics)	1	0-3
Processing for products and traceability	1	3-6, 6+
Packaging & post-harvest operations (including quality and disease mgmt)	1	3-6, 6+

[a] High (3) to low (1)
[b] Years: near term (0-3), medium term (3-6), long term (6+)

While this perspective covers food safety and consumer choice benefits, it fails to acknowledge other benefits that a broad definition of traceability might offer. If traceability is defined to involve pairing each food product with an information history (dynamically collected), then we can project numerous direct and indirect benefits. In this view, purchasing any food product would also include buying the information that describes: its place of production (possibly even grower information), production parameters (how it was grown, e.g., sustainably, organically, free range), processing parameter (e.g., location, certification), product environment during shipping, handling, and storage, time on retail shelf, time since harvest, bacterial count warnings, etc. With appropriate sensors on the food product/packaging, or in the farm-to-fork stream, along with information storage on the product or its packaging, regulatory agencies, wholesalers, retailers, shippers, and the consumer can have much bigger roles in the food system.

Table 4. Future sensor and sensor network R&D, based on industries needs.

Issue/need/concern	New knowledge/technology/capability
Water management	Runoff and waste water; plant-level water mgmt: soil moisture, plant water use
Food safety	Need sensors for: chemical and microbial contaminants, defects, and allergens
Disease/pest management	Need sensors for: soil pests, spray efficacy, pest detection, and phytosanitary plant condition
Product quality	Need sensors for: sorting & grading, sugar content, pests, sensory attributes, traceability, inventory control
Crop management	Need sensors for: yield, maturity, soil and in-plant nutrients, plant health, canopy management
Crop harvest	Need sensors for: yield, maturity, fruit location, mobile platform tracking, dexterous manipulation, inventory tracking, quality mapping

All the aforementioned actors can exert greater control over how food is produced and delivered by the decisions that they make. By favoring certain brands over others (that employ particular production or processing methods), downstream actors can indicate how food should be produced or processed. This could lead to greater (or perhaps lesser) adoption of sustainable production practices by growers and processors. Downstream choices may also signal which producers are favored over others. There may, for example, be a trend to prefer locally grown products over products shipped long distances. This would in turn promote a less transportation-dependent and more sustainable food system. It would also impact *food security*, as there would be a greater variety of producers with greater geographic dispersion, leading to increased redundancy in our food systems and making them less susceptible to disruption. There may be many other direct and indirect impacts of information-dense traceability, depending on exactly what information becomes available.

Will downstream actors make those cognitive choices? Obviously, regulatory agencies will use food product information to do their jobs more effectively and business enterprises will use it to improve their bottom line. How about consumers, though? The answer is that some will and some won't; food is currently too cheap and too readily available that many consumers don't view such choices as important. Many don't read food labels now (forgetting for a moment that a chemistry degree is required in some cases). When the character of food changes—either with regard to cost or quality—then the average consumer will take notice and begin making more informed decisions. Traceability information will then become more useful to a broader spectrum of consumers.

There is also obvious benefit for agro-security to having more sensors with increased capability. This applies not just to intentional or unintentional contamination of food shipments, but also could include better detection of insect and disease pests. Invasive species are a major concern throughout agriculture, forestry, and ecology. Reducing invasions into this country through better monitoring of shipping containers and products and limiting their movement could have major, long-term impacts.

The tight integration of agricultural products, sensors, and information inherent in the view of traceability described above provides a very important example of the interplay of biology and engineering. Information about an ag product is sensed and stored (very likely on the product or its packaging). These engineered sensing and information storage components then convey that information to the downstream actors so that they can make decisions about the ag product, e.g., discarding due to spoilage, purchasing for consumption, distributing to a particular market, etc.

Issues

The final emphasis area that I'd like to touch upon deals with how we go about development and application in biological sensorics: environmental responsibility, training professionals, research approaches, and application development.

<u>Social & Environmental Concerns</u>

I was encouraged to see the topic areas for this conference include societal and environmental issues. Such things need to be part of long-term planning for any new technology area. We need to be concerned with, and eventually understand, technology impacts on various aspects of society (both positive and negative) and also how different segments of society might view and adopt these innovations. New technology is never adopted uniformly and that can have dramatic consequences for social, political, and legal institutions. Technology impacts on society are sometimes obvious, but much more often they have many subtle implications as well. While it is probably impossible to anticipate all the more obvious ones—and certainly the less obvious ones—it is important to look for patterns early on and to use what we know about similar, past innovations.

Once some of the earliest characteristics of nanomaterials became apparent, researchers began looking into their interactions with living organisms. That work has led to the development of more bio-benign nanomaterials, attention by regulatory agencies, and better safeguards for their manufacture and use. Certainly introducing small sensor and information tags directly onto agricultural products for traceability purposes or embedding large number of micro-electromechanical systems into forests or agricultural fields will bring about many similar concerns. In addition to similar human or ecological risk studies, it may be necessary to develop education programs to inform ag producers, consumers, and the food industry about what new traceability technology or new sensor networks are, and what they are not.

Developing and deploying a suite of new technologies will change those areas were it is applied, e.g., food distribution, apple production, etc., in very dramatic ways. Not only will R&D require students and researchers with different skill sets than in the past, it will require a better trained and more technologically savvy workforce. This suggests that we need to attract more scientists and engineers into the field of biological sensorics and to provide more responsive, local training for the agricultural worker. A two-tier educational system may be needed. At the academic, degree-granting level, we need to better differentiate between the type of coursework provided to agricultural technicians and managers (associate-degree level) and agricultural researchers and scientists (baccalaureate and higher). At the field level, we need better training for the agricultural worker. This training needs to be readily adaptable to changing local issues, technologically current, and responsive to specific application industries.

Systems Science & Engineering

More and more, federal and academic research entities are being held accountable for meaningful outcomes from funded research, especially when that research is publicly supported. Accountability may be driven by expectations of state or national stakeholder organizations, by legislative bodies, or by the public. Such increased scrutiny does not necessarily threaten basic, fundamental investigations, in favor of applied research with readily tracked impacts, but it does force research entities to carefully elucidate the scientific benefits (e.g., expanding the knowledge base) and future commercial value (e.g., patents, disclosures) of what they do. When future research support is tied to past performance, in this context, research organizations take notice quite quickly.

Aside from the accounting procedures and mechanisms that can be employed to deal with these new world realities, there are things that we as researchers, program managers, and administrators can do, also. By proactively and effectively using collaborations, funding and performance incentives, programmatic innovations, and partnerships, we can conduct research has more problem-solving capacity *ab initio*. And, what gets attention and headlines are successfully solved problems.

There has been talk for years about the limitations of disciplinary-based science. Using the traditional model of scientific development, one can very effectively build a body of science that explains a set of phenomena. Theories are developed through observation, and experiments are conducted to support or contradict those theories or to further refine them. Over time, the necessary scientific structure develops to support broad understanding of a discipline. However, when faced with problem solving in a real world context, there's no mechanism available within disciplinary-based science for generating viable solutions and for testing them. The real-world problem-solving context involves externalities that are not part of any well-constructed discipline in isolation. What is needed for solving problems is a broader, multi- and inter-disciplinary perspective that takes into account the full system within which the problem resides. Furthermore, we are not, in most instances, talking about an entomologist working with a pathologist working with a plant physiologist, for example. Truly dealing with all facets of a problem—and to have a chance of solve it—more often means merging the bio-physical with the social and economic aspects of problems to arrive at a systems solution. It requires that scientists collaborate "outside their species," so to speak.

Figure 1 contains a systems-based diagram for the food production, processing, and consumption system. It consists of a hierarchical taxonomy of systems. The primary food systems—crop production, processing and distribution, and consumers and markets—which in total define a "producer-to-consumer" system, appear at the highest level, with more specific subsystems found within each. Emphases for impact-oriented research efforts would focus on an entire primary system or where two or more of the primary systems overlap/intersect. At the most specific level of the hierarchy, one finds traditional, disciplinary research, development, and application efforts (focused science and application studies), which are also integral to this system perspective. With sustainability outcomes and impacts as an umbrella goal, all critical disciplines, world views, and approaches can be incorporated into a broad-based solution set.

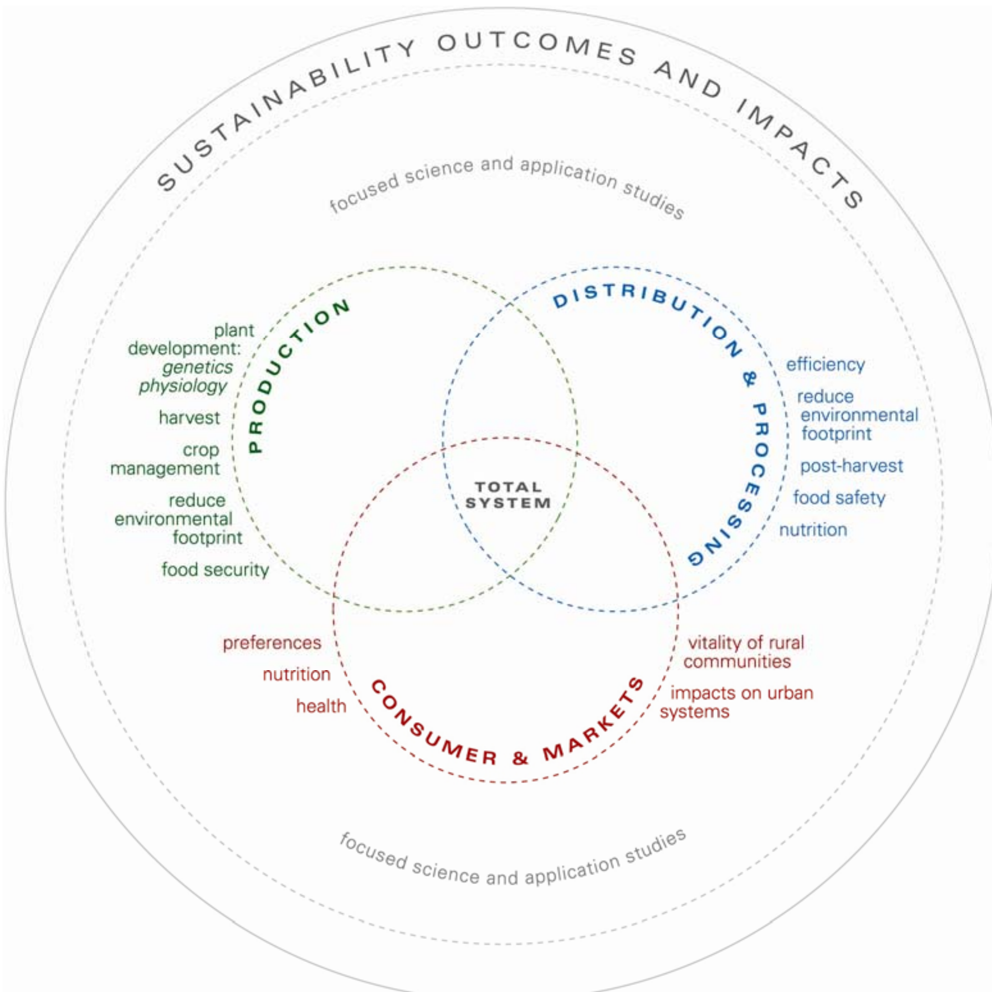

Figure 1. Under the umbrella of sustainability, an agricultural systems approach contains three interacting *primary* systems: production, processing, and consumers. Within these three primary systems there are subsystems and focused scientific studie. Except for the most narrowly focused projects, social, economic, and bio-physical aspects would be included in most projects.

Final Thoughts

As skilled and committed researchers, it's easy to get bogged down with the daily minutia and details of complex R&D projects. From time to time, though, it's important to step back and examine what it is we are doing, and why. Who benefits and how? In what ways can we inch those potential benefits closer to reality? It is my hope that you will take an opportunity to introspect here at this conference, either sparked by something that I've said or based on off-line discussions with colleagues today and tomorrow.

Again, this is a conference that is both "timely" and long overdue—if that's not too self-contradictory. I congratulate the organizer for their initiative and hard work to make this happen. There is a tremendous volume of excellent work going on out there in traditional ag/food/environmental areas, but also in non-ag areas. I fully expect that future renditions of this conference will see an even great infusion of different biological sensorics participants from outside traditional ag disciplines. Such cross-fertilization is absolutely critical as we marshal broadly based resources and bring them to bear on extremely important problems in natural resource management and in our food systems.

Great engineering abounds in the biological world. But, it's not just apparent in structures and materials, such the spider's web. It's there in processes of social organization and in behaviors that are honed by evolution to be correct most of the time, while still being resilient and tolerant of faults. These features define the very core of the evolutionary process itself…There exists a great test bed of engineering models out there that have proven themselves over thousands of years to be valuable and remarkably successful. I would encourage you to seek them out, learn from them, and adopt their best features for incorporation in the work that you do. There is both parsimony and elegance in the natural world; these are great qualities to carry over to *your* engineering efforts.