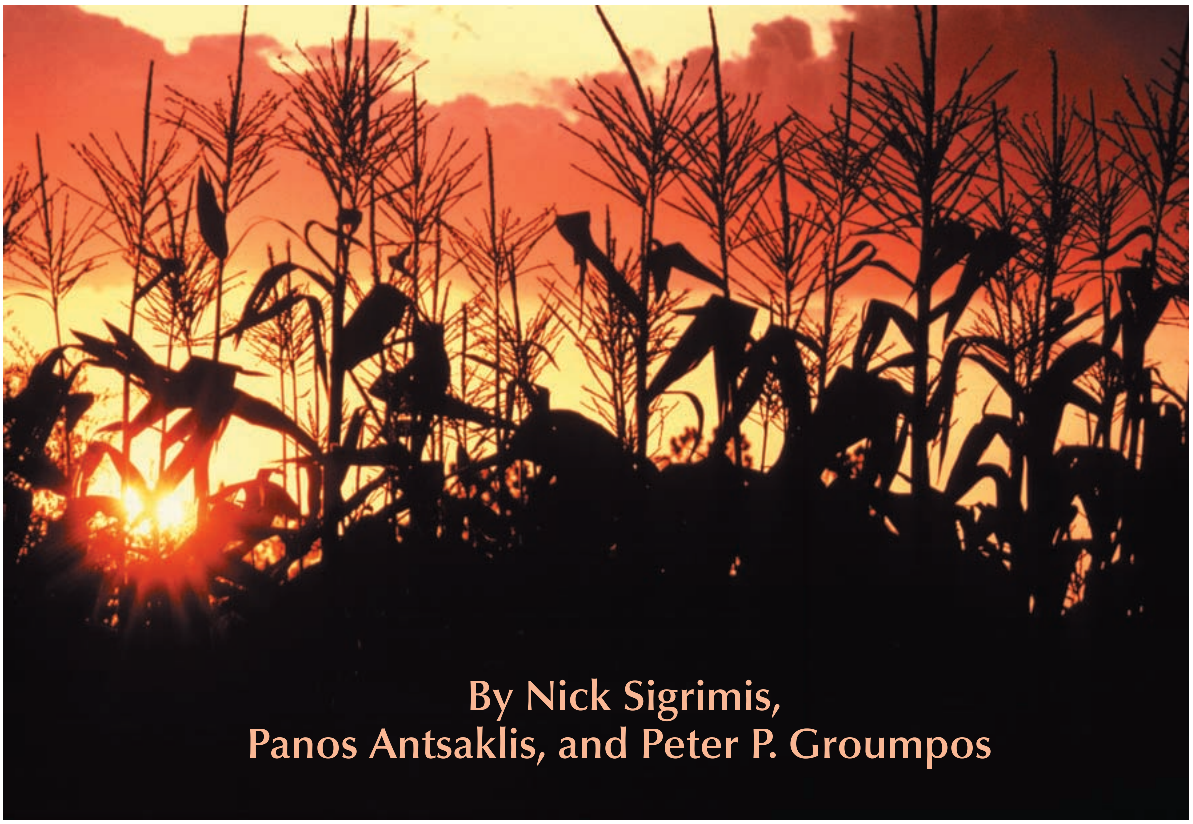
Advances in Control of Agriculture and the Environment



By Nick Sigrimis,
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The agricultural sector is rapidly being transformed into an industry of major importance that must rely heavily on computer-integrated management and advanced control systems. These technologies are becoming essential components of the next generation of plant and animal "factories" in the new millennium. Efforts are being undertaken to survey the technological landscape and recognize trends shaping this upcoming application field.

Modern agribusiness is becoming increasingly reliant on computer-based systems, automation, and robotics that are taking over many of the tedious tasks formerly performed by humans, with superior performance in most cases. To manage the increasing complexity of agricultural systems, increasingly sophisticated methodologies are required. This has given rise to the promising field of precision agriculture, where the goal is to improve the efficiency of operation of agricultural enterprises, as well as the quality and consistency of products, by compensating for the vague-

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Sustainable Development

The world is in transition to one in which there will be more people, greater consumption of materials and resources, more global interdependence, and a need to reduce poverty without destroying the environment. Over the past two decades, "sustainability" has become a principal concept in integrating technological, economic, social, and political issues to address environmental protection and economic development. The future depends on harnessing the power of modern technologies, consistent with the interests of the poor and hungry, and with respect for the environment. Agriculture, as a source for food, natural raw materials for bioindustries, and energy, will increasingly be a major driver of this transition.

"Definitions" abound for sustainable development. I prefer to think of it as a "process" of redirection, reorientation, and reallocation—an evolving process rather than a static definition. I see sustainable development as a fundamental redesign of technological, economic, and sociological processes to address change. To get beyond the various images of sustainable development, there is a need to develop a "science" of sustainability and systems of implementation. This leads me to suggest that the process of transition to a sustainable world will include:

- Streamlining processes and reusing materials with a goal of zero waste.
- Embracing new technologies of information science, biotechnology (genomics and integrative molecular biology), and advanced materials to reduce environmental problems while increasing economic productivity.
- Utilizing renewable resources for energy to reduce or eliminate our dependence on fossil fuels.
- Developing sustainable communities based on the efficient use of space, increased conservation of materials and energy resources, and reduced transportation.
- Improving community livability and developing more efficient administrative and planning processes to demonstrate ecological living that is economically and socially desirable.
- Developing sustainable agriculture as a principal component of sustainable communities where use of fossil fuels, insecticides, herbicides, and inorganic fertilizers is minimized or eliminated.
- Focusing on newer and innovative sustainable enterprises such as bio-based industrial products.

The challenge is to rethink how the material needs of society can be met by using agriculturally based systems. This rethinking involves an integration of science and engineering with an emphasis on ecological processes and socioeconomic phenomena. Technologies such as biotechnologies, information systems, and control and management systems will play a key role in inventing new processes and ensuring their effective and efficient execution (at the highest possible quality and lowest cost).

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ness and uncertainty of the environment. Conversely, social demand has created pressure for respectful treatment of the environment and the well-being of humans. These objectives result in new and challenging problems—problems that can only be resolved by applying advanced information and control technologies to production management of processes and farms.

Agricultural production management systems are becoming highly sophisticated and are beginning to exploit many of the advanced methodologies and tools of industrial automation, modern control theory, and manufacturing. Closely linked to these developments are electronics and communication technologies. In addition, the biotechnology revolution promises dramatic improvements in production efficacy that we hope will also meet social and societal concerns. At the same time, systems engineering is taking on the challenges and complexities involved in managing complex agricultural systems and is actively pursuing systems capable of that elusive property, intelligence. Such interdisciplinary activity cannot help but lead to more effective agricultural systems that will be essential for sustainable, quality production in the new millennium (see "Sustainable Development" above).

Historical Perspective

Agriculture is the oldest industry, dating back to the nomadic age. It initially depended solely on human labor, then captured animal power, and followed next by reliance on mechanical developments such as steam/diesel-engine tractors and mechanical implements with hydrostatic power where control was needed for attached implements (see Fig. 1). To date, most mechanization problems have been solved from the mechanical point of view. The solution of unsolved problems depends on further improvements that require the replacement of human intelligence to meet the needs for greater autonomy in more unstructured and uncertain environments. Human intelligence entails sensing, perception, prediction, planning, proactive response, and feedback. Promising fields in this context include mechatronics, complex system automation, and large-scale optimization. Necessity is driving the absorption of information technologies into agricultural technologies, whether in the guise of a machine, a process controller, or a planning and management system. This is evident from the shift of ongoing academic and industrial research in this field, as presented in the invited articles in this special section.

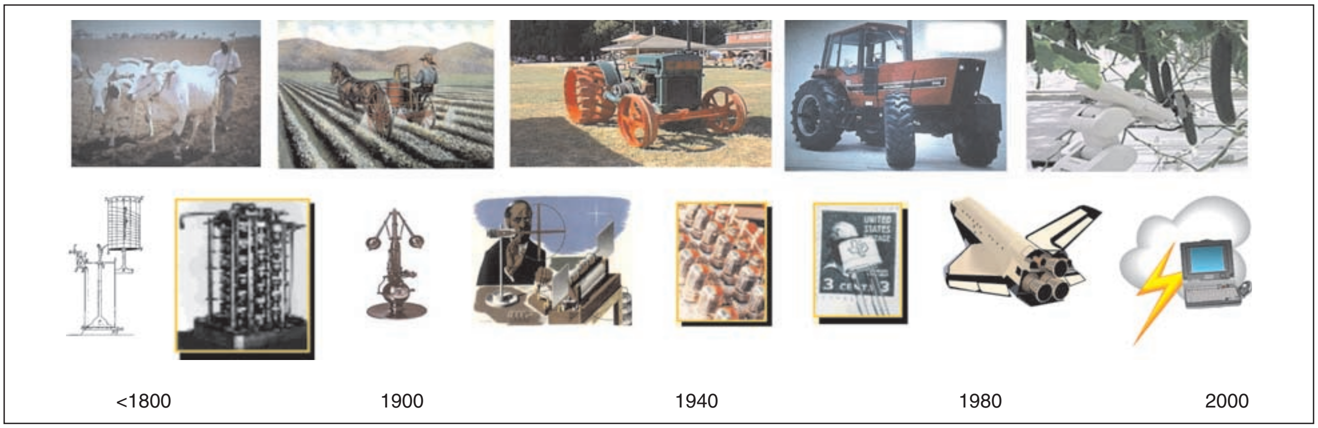

Figure 1. *Historical evolution of agricultural technologies in relation to information-communication-control technologies.*

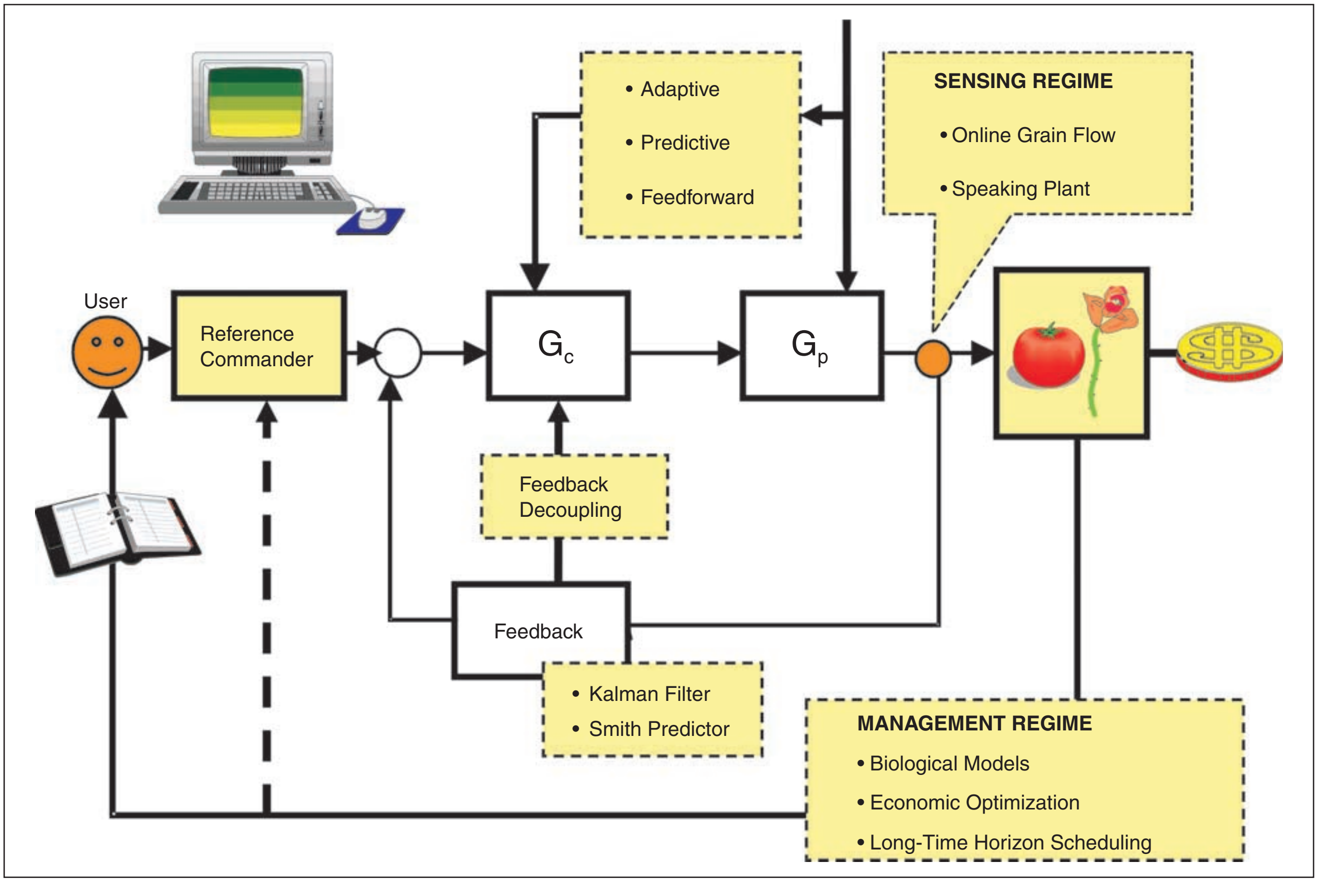

Figure 2. *Advances in control loop components presented in this special section.*

Scanning the Issue

Recent research has resulted in advances in all technologies bound to the closed loop as well as to the outer loops necessary to meet higher autonomy and precision (see Fig. 2). The articles in this special issue address several of these advances and represent a sampling of current research activity in the field of crop management and control. The knowledge components necessary to deploy advanced controls and computational intelligence in crop production include a variety of forms such as models, fuzzy reasoning, and evolutionary algorithms, as well as technologies and implementation platforms such as mechatronics, networked systems, and robotic systems.

Data-Driven Modeling

The first article, by Young and Chotai, provides an overview of conventional modeling methods used in the environmental and agricultural sciences and introduces a new data-based mechanistic (DBM) approach. Mathematical modeling and control techniques in the environmental and agricultural sciences are often dominated by a philosophy of deterministic reductionism. Moreover, many of the "simulation" models that emerge from this approach are very large and difficult to identify, estimate, and validate in rigorous statistical terms. This article considers alternative stochastic modeling strategies developed to obviate some of these problems and produce parametrically efficient models that reflect the "dominant modal characteristics" of the system.

The importance of these DBM models, which can be linear, time varying in parameters, or nonlinear in form, is that they provide an appropriate basis for advanced, multivariable control and forecasting systems. In the early stages of such a design process, when observational data are either scarce or not available, the DBM modeling methods can be used to obtain reduced-order versions of the large simulation models, which then allow for initial control or forecasting system design. Subsequently, as experimental or monitored data become available, these same methods can be used to identify and estimate stochastic models that both represent the modal dynamics and quantify the inherent uncertainty associated with the system. As a vehicle for control system design, these models are then used to formulate a nonminimal state space representation of the system, which provides the basis for the design of multivariable control systems. In the case of forecasting or "data-assimilation" applications, the DBM methods are used to define an "unobserved component" representation of the data. This then allows for the implementation of Kalman-filter-based, recursive forecasting and fixed-interval smoothing algorithms, whose statistical "hyper-parameters" are optimized in maximum likelihood terms using prediction error decomposition techniques.

This approach to modeling, control, and forecasting system design is generic and has wide application potential, and the authors illustrate its practical utility with several examples, ranging from the modeling and control of microclimate and ventilation in agricultural buildings to the design of adaptive flood forecasting and warning systems.

Plants in Space

The next article, authored by Albright et al., examines some implications of combining biological and physical models to control the root and shoot environments of plants grown in greenhouses, specialized growth rooms and chambers, and advanced life support systems such as those under development by NASA.

Environmental control for living systems differs greatly from comparable control for physical systems. Environmental requirements for living systems are typically more complex and nonlinear, and the biological system is likely to have significant and numerous effects on its physical surroundings. Moreover, greenhouses and other natural-light growth facilities must be controlled to deal with rapidly changing solar loads. Plant production systems often lead to problems that are more related to load control than to traditional set-point control. The problems may be exacerbated in the reduced-gravity conditions of space, where thermal buoyancy effects, plant morphologies, and cost considerations can be very different.

An important extension of these recent developments is likely to be an enhanced ability to provide real-time and adaptive fault detection systems to identify the onset of biological system upsets. This advance will be particularly important for space applications where constant plant care, such as provided in earth-based greenhouses, will not be practical.

The authors provide an example of a MIMO nonlinear system with nonconstant disturbance-affected actuator constraints for the evaporative cooling of a greenhouse physical climate. The approach taken is to use a precompensator to define an admissible operating set and a search mechanism to locate an optimal set-point vector, along with an in-the-loop feedforward/feedback linearizer and decoupler leading to noninteracting controllers for each of the output variables.

Toward Precision Agriculture

Severe global competition with sharp price increases for raw agricultural products and heightened concern about the environment force farmers toward more appropriate use of resources for field crop production. In this respect, manufacturers, in close cooperation with leading research groups, began developing intelligent agricultural machines for precise and site-specific field operations, integrating mechanical, electronic, computer, and information systems.

De Baerdemaeker et al. describe advanced mechatronic designs for three different mobile agricultural machines. A yield-mapping system for a combine harvester requires the design of the necessary sensors and processing of the acquired data. The latter includes aspects of filtering, elimination of unusable data, and compensation for machine dynamics. To reduce chemical inputs for plant protection, field sprayers are equipped with an intelligent selective spraying system. Optical sensors, detecting weeds among field crops, activate the appropriate pulse-width-modulated nozzles, mounted on the spray boom. The nozzles are correctly positioned in the field by stabilizing the spray boom with an active suspension.

To improve and ease field operations, especially in row crops where the distance between rows and between plants within a row must be extremely precisely regulated, the steering mechanism of the agricultural machine is controlled by a reliable navigation system. The latter fuses data from several dead-reckoning sensors and in combination with global positioning systems. The communication system is the backbone for the tractor-implement as well as for the tractor-farm computer transfer of the large amount of data needed for precision agriculture. Control problems in the high-precision spreading of liquid manure are also addressed. The system developed for this purpose makes use of an extended Kalman filter and a Smith predictor.

A Japanese Perspective

In the last article, Hashimoto et al. present a sampling of Japanese research in intelligent agriculture control. First, the latest biosystem-inspired optimization algorithms are discussed. The authors describe a finite-element inverse technique that employs neural networks and a new photosynthetic algorithm; a comparison with genetic algorithms is outlined. Another new technique, leaf cellular automata, is also introduced, and its application to optimization problems is discussed.

Second, a decision system consisting of neural networks and genetic algorithms is applied to the optimization of plant growth in hydroponics cultivation. Plant growth dynamics, as affected by nutrient concentration, were first identified using neural networks. Then, using genetic algorithms, the optimal one-step-ahead nutrient concentration set points that maximize plant growth were determined through simulation of the identified neural network model.

The last topic of this article is intelligent agricultural robots in Japan; a survey of various machines and application areas is provided.

Conclusion

Recent advances in sensing, information, automation, and control technologies are providing researchers with means to explore previously unanswerable questions regarding plant physiological requirements. The ability to provide specialized environments, together with emerging diagnostic techniques for cellular differentiation, segmentation, and elongation, as well as whole-plant imaging, open further avenues of research. The fruits promised by this research include improved basic understanding of physiological processes and enhancements of our ability to apply this knowledge in efficient production control systems.

Domain knowledge from research results must be coupled with technological implementation to ensure fast exploitation; the demands for shortening product life cycles need to be addressed. Although no one can claim that intelligent control is a panacea for every conceivable control problem in agriculture, it must be seriously considered in future developments. The objective here is to exploit the tolerance for imprecision and uncertainty that are hallmarks of computational intelligence techniques while incorporating characteristics of the agricultural environment under a requirement for rapid implementation. Given the power of soft computing and the wide acceptance of conventional manufacturing and control approaches, the question arises as to how to best benefit from both worlds.

At the level of management, many production operations are event based, and the need for conflict management and efficient scheduling has become apparent. Manufacturing technologies such as discrete-event systems and lattice theory must migrate to field production and supply chain management operations. Can we develop solutions using hybrid systems to realize new control accomplishments for the benefit of society? Can the hierarchical approach, based on synergistic/competing intelligent agents using layered subsystems of intelligent supervisors providing command-level directives for conventional controllers, yield solutions to some of the pressing problems in the field? We believe that such hybrid systems, which can make best use of existing as well as new knowledge about the process, will open up new horizons and lead to even further developments. Our challenge is to find practical solutions to the complex problems faced by society in the control of agriculture and the environment.

For further study the reader is encouraged to consult, in addition to the references cited in the invited papers, the following publications:

- Special issue on "Computational Intelligence in Crop Production," R.E. King and N. Sigrimis, Guest Eds., *Computers and Electronics in Agriculture*, vol. 31, no. 1, 2001.
- Special issue on "Artificial Intelligence in Agriculture," H. Murase, Guest Ed., *Computers and Electronics in Agriculture*, vol. 29, nos. 1-2, 2000.
- Special issue on "Advances in Greenhouse Environmental Control," N. Sigrimis and R.E. King, Guest Eds., *Computers and Electronics in Agriculture*, vol. 26, no. 3, 2000.
- *Proceedings of the IFAC Int. Conf. on Modelling and Control in Agriculture, Horticulture and Post-Harvest Processing*, Wageningen, The Netherlands, July 10-12, 2000.
- Special issue on "Environmental Applications of AI: Toward a Balanced Use of Nature's Resources," *IEEE Expert*, vol. 10, no. 6, 1995.
- J. Bryzek, K. Petersen, and W. McCulley, "Micromachines on the march," *IEEE Spectrum*, vol. 31, no. 5, pp. 20-31, 1994.

The guest editors believe that, since agriculture is undergoing a business transformation and since enough science has been accumulated in the process domain over the years, eventually control and management systems will rapidly expand the frontiers of this application field. Readers are kindly asked to express their opinion about the usefulness and coverage of this issue to any of the guest editors:

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