A Multi-agent System for Integrated Production in Greenhouse Hydroponics

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Abstract
The design of a multi-agent system <MAS> for integrated management of greenhouse production is described. The model supports the integrated greenhouse production, with targets set to quality and quantity of produce with the minimum possible cost in resources and environmental consequences. The main goal is the Integrated Crop Management (ICM) of root-zone and aerial environment of the cultivated plants, through the cooperative actions of software agents, which bargain at the supervisory level. The conventional management systems have the drawbacks of being based on low level, static, user-defined goals, as they do not take into account the interactions between processes or they do it either in the LQG domain or in a non-systematic ad-hoc way. The poor performance when existing conditions lead to conflicting decisions of the control system, or irrational use of the resources can be drastically improved by the ability of the MAS-GH system to allow “humanwise” perception and decision processes in an easily reconfigurable environment. The system evolves by means of accumulated knowledge as tools are endowed for “agents’ experience” or research results or growers’ experience.

INTRODUCTION
Biological systems in artificial environments, consist of complex, not exactly defined, interacting processes. Those systems are usually treated with optimal control strategies that are applied separately to each process (Linker et al., 1999; Pasgianos et al., 2003) and not to the entire system as a whole. Some attempts to approach the multivariable optimization problem in the LQ domain (Sigrimis and Philippopoulos, 1984; Young et al., 1994; van Straten et al., 2000) can only cover but a small span of the scope addressed by this new effort. Several aspects of artificial intelligence have been applied to modeling and control of these systems, such as neural network modeling of greenhouse climatic parameters (Seginer et al., 1994) or of hydroponics parameters (Ferentinos and Albright, 2002) and combination of neural networks and genetic algorithms for fault detection and diagnosis in hydroponics (Ferentinos and Albright, 2003; Ferentinos et al., 2003). The treatment of individual processes of a complex system, especially when those processes often conflict with each other as in the case of greenhouse climate and hydroponics control, does not necessarily lead to the optimal solution of the entire system. The definition of set-points and constraints for the control of such systems is difficult and problematic. In addition, each process may contribute to a different and changing degree to the final output of the system. In such cases, each process can have each own local dynamic control system, optimally tuned to the local goal, which is defined in a general environment, taking into account the final output of the entire system.

One approach for the optimization of such systems is the use of learning techniques such as backpropagation learning (Rumelhart et al., 1986) and reinforcement learning (Kaelbling et al., 1996). Another approach, traditional but nearly identical in control span, is the development of interaction variables for all processes, which form a hierarchical rule-based system. This is trying to optimize the operation of the final system through the defined structure, as it has been practiced in Large Scale Systems. On the other hand, the multi-agent method (Talukdar et al., 1992; Sykara, 1995; Stone and
Veloso, 2000) creates a non-structured environment using the so-called agents, each of which represents a process and its local goals. These agents, in order to reach the global optimum, must be capable of performing transactions between each other, achieving several “deals”, which is performed through a common vocabulary, a finite set of information exchange, a finite set of possible actions, penalties, etc. (Kelemen and Kelemenova, 1992). The power of each agent depends on the degree of contribution of its represented process to the final output of the entire system. Each agent communicates with the “environment” and adapts to its own internal state as well as to the state of the entire system.

Multi-agent systems (MAS) are based on the general concept of distributed processing through autonomous computational tools. Da Silva and de Lucena (2003) propose a conceptual framework that defines the structural and dynamic aspects of such systems. This framework extends the widely-used UML (Unified Modelling Language) to incorporate concepts to MAS theory, building an alternative MAS modelling language (MAS-ML). Mapping the design elements at the agent level of abstraction to MAS-ML programming language clearly defines and represents all the elements that compose multi-agent systems including an analysis of existing agent and object-oriented programming languages to support MAS implementation. The definition of the interaction mechanisms between agents via the communication language and vocabulary is very important. Finin et al. (1992) introduced KQML (Knowledge Query and Manipulation Language), a language and protocol to support interoperability among intelligent agents in a distributed application, attempting to define its scope and providing a model for how it will be used. Labrou and Finin (1994) investigated the semantics of KQML and proposed a semantic framework for the language investigating implementation issues to their approach. Very recently, d’Inverno et al. (2004) presented the dMARS architecture which extents the Procedural Reasoning System (PRS) currently established, which will enable agent implementations to be easily developed and will serve as a benchmark against future architectural enhancements.

AGRICULTURAL APPLICATIONS OF M.A.S.

Multi-agent systems have been used in a wide range of applications, like control issues in robotics, distributed systems in telecommunications, intelligent e-commerce systems, artificial intelligence applications, etc. Recently MAS have also been used in biological and agricultural applications. Rousu and Aarts (2001) presented an approach used in Sophist, an adaptive recipe planning system, which integrates case-based reasoning for the design and optimization of bioprocess recipes which may improve the system’s adaptivity. Perini and Susi (2002) adopted the Tropos methodology, described in Perini et al. (2001) and in Giunchiglia et al. (2001), an agent-oriented software development methodology, in order to design a MAS devoted to support decision making by the technicians of the agricultural advisory service when managing plant diseases. Davidsson and Wernstedt (2002) introduced agent theory and implementation, categorized and described agents depending on their tasks in reactive, deliberative, hybrid and wrapper agents. Agent interaction and development for multi-agent systems were discussed along with describing applications of multi-agent systems in monitoring and control. It also summarized the main arguments for choosing MAS-based approaches. Badjonski and Ivanovic (2000) described a MAS implementation which tried to imitate human experts for the determination of optimal hybrids in crop production. The system’s architecture was composed of 8 agent modules named: Climate-agent, Group-agent, Purpose-agent, Evaluator-agent, Soil-agent, Disease-and-Pests-agent, Mechanization-agent and Interface-agent, exchanging messages with each other using a simple communication scheme. Partially compared with its rule-based predecessor there was no major observed improvement in performance, but advantages of the proposed approach have been noticed in system construction and modification and in organizing the development process. In the area of greenhouse management, Prada et al. (2004) described their agent-based application (BeLife) which simulated greenhouse plant
growth management and the software platform developed for building the agent’s simulation namely ION-Framework. BeLife was designed as an educational tool teaching greenhouse management from where students can inspect and modify some conditions and elements of the world in a collaborative manner. In the same field, Goggos and King (2000) presented a technique of partitioning the overall process of greenhouse management to sub-processes (agents) linked through a coordinator process. The design procedure used qualitative descriptions of the attributes of the closed system performance. Recently, Barreteau et al. (2004) demonstrated a potential use of agent-based modelling frameworks for simulating the irrigation system and researching on its viability in the Senegal River Valley.

MATERIALS AND METHODS

The management of greenhouse hydroponics facilities includes several physiological processes that influence the growth of plants, such as lighting, temperature, humidity, composition of nutrient solution, etc. The value of the final product incorporates not only quantity issues but also quality issues, which are difficult to be measured or even estimated. The environment of each agent is defined by the same parameters that define the physical environment in addition to internal states reported by each agent (Fig. 1). The agent’s possible actions are defined by the available mechanisms and actuators and their effects to the environment. Thus, each controlled process of the greenhouse environment is modeled as an autonomous agent with its own inputs (its corresponding measured environmental parameters), its own outputs (the energy signals at its corresponding actuators) and its own interactions with the other agents. Each agent acts autonomously, as it knows a priori the desired environmental set-points. At the same time, there is cooperation between the agents, as all greenhouse environmental parameters are influenced by each other. In many cases there are controllability issues as the same actuator is used to control different variables, which may be in contradiction (i.e. ventilation for humidity and temperature). In this way, any possible conflicting decisions of conventional environmental control methodologies are resolved through negotiations between the agents so that the possible optimal integrated solution is achieved.

The negotiations between agents are subject to optimization based on “knowledge” that is derived from complete production models, yield models or even sparse models as expressed in fuzzy expert rules or practical rules of thumb. In addition, pest control and plant disease models provide additional information useful to the design of a successful strategy for optimal management by the MAS-GH (Fig. 2). The major dilemma is how to exploit “knowledge” of different forms; whether it is more efficient to add capacity to agent’s intelligence for the deployment of different knowledge sources or design an intermediate layer of knowledge acquisition, elicitation and “homogenization”.

The “environment” of the agents, hereby called a-environment, is characterized by the model of the physical system and its reaction to inputs, the production targets as expressed by the “user-goals” and the “production-knowledge” that guides the climatic environment, hereby called c-environment, to the targeted goals. The complete agents “environment” is shown in Fig. 3. Each agent receives the necessary environmental or plant condition measurements. While each agent keeps its autonomy and has its own “personal” goals, it interacts with the other agents through some specific communication language, in the “Agent discussion area”, where the overall goal is taken into account. This interaction takes place under the presence of information from the existing models (Fig. 2) and the target goals. At that point, each agent has decided on its best strategy. However, conflicting decisions are very probable to arise. Several computational and analytical methodologies, such as fuzzy logic (Zadeh, 1965), descent methods and evolutionary algorithms (Fogel, 1995) are used to resolve conflicts and reach to some final decision.
INTEGRATED PRODUCTION SYSTEM

A specific arrangement of the MAS is the one where each agent corresponds to one of the main controlled parameters of the physical system. These can be divided into two groups, the environmental agents (temperature, humidity, CO₂ concentration, solar radiation) and the hydroponics agents (pH, electrical conductivity, dissolved oxygen, salinity, water available, temperature of nutrient solution). When two or more agents enter the “agent discussion area”, they exchange information about their state and they inform the other agents about possible actions that have to be taken in order for each agent to achieve its goals. For example, during hot and dry weather conditions, the temperature agent has a value greater than the temperature setpoint, which leads to consultation of “user goals”. At the same time, the humidity agent has a value smaller than the humidity setpoint and thus it decides to keep the windows rather closed. At first level these two coupled variables call a specific T-H resolver, the PCG used in Sigrimis T-H, to compute required ventilation and humidification. On return the system realizes that “fog does not exist” and the agents bargain about the optimal ventilation rate, taking into the “cost” the risk from pest models. That is, these two conflicting decisions are fed into the “conflict resolution scheme”. There, an optimization algorithm that takes into account the user goals and the outputs of the existing production, yield, plant diseases and pest control models, estimates possible consequences and results from several scenarios and the optimal resolution is found about the optimal ventilation rate. According to this result, a final decision is taken. This decision can have either the form of some actuator command or of some adaptation of a setpoint value.

The models that help in the MAS’s decision-making process use information from the measurements of the physical system. They also use information from potential actions after some agent’s decisions in order to forecast, for example, the potential for the appearance of some disease, or the increase of some pest population, or the future yield response, or the total quantity of production. This predictive information is crucial to the conflicting resolution scheme and leads to better control strategies and integrated management. Currently there is an effort under way to produce an ontology which will encode the knowledge about pest and disease biology, nutrition requirements and potential yield of certain variety, resistance to diseases of the cultivated variety etc. This ontology, separated into pests bio-behavior, and plant’s susceptibility and nutrient requirements, will be used by the agents to draw knowledge and carry on their assigned task. The aim is to produce a functioning system which will last through the technological changes and will be open to fine tune and augment the ontology built, with better knowledge drawn from research or new pests added etc.

The basic features of the multi-agent system are the following:
- It’s an open system with high degree of adaptation to different kinds of products, as well as to different types of biological production (animal production, pisciculture, precision agriculture).
- It can be easily expanded with the addition of new agents or the definition of new entities in the MAS ontology and new management goals.
- It can cooperate with other low-level greenhouse management and control programs by a simplified data exchange through sharing a whiteboard.

CONCLUSIONS

A multi-agent system methodology for integrated management of hydroponic cultivation systems in greenhouses was proposed. Several autonomous agents interact in order to resolve conflicting decisions that could lead to ineffective control and management of the greenhouse production system. The application of this multi-agent approach to the optimization of the integrated management of root-zone and aerial environment leads to the following results:
- Resolution of conflicting control decisions in complicated situations during plant growing
- Development of a knowledge-base system (numerical models, fuzzy rules, etc.) that leads to the management with integrated goals for the consumer (security, quality) and the environment (minimization of chemicals).
- Application of a complete system for product certification for integrated production.
- Analysis of the production processes as far as nutrition and photosynthesis are concerned, and of the conditions that affect these processes.

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Literature Cited


Fig. 1. The multi-agent overall environment for integrated management.

Fig. 2. Multi-agent system information and knowledge scheme.
Fig. 3. Structure of the MAS for integrated greenhouse hydroponics management.