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Mechanization, Automation, and Computerization for Greenhouse Production

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Summary. **Availability and capability of labor have become dominating factors affecting agriculture's productivity and sustainability. Agricultural mechanization can substitute for human and animal physical power and improve operational uniformity. Automation complements mechanization by implementing the capabilities of automatic perception, reasoning, communication, and task planning. Fixed automation is traditionally cost-effective for mass production of standard items. In addition, flexible automation responds to make-to-order batch processing. The appropriateness of each automation type depends on the situation at hand. Because of their vast memory and high calculation speed, computers are highly effective for rapid information processing. Incorporating state-of-the-art hardware and software, computers can generate status reports, provide decision support, gather sensor signals, and/or instruct machines to perform physical work. It is no surprise, therefore, that computerization is essential to the evolutionary process, from mechanization through fixed automation to flexible automation. Fundamentals of agricultural mechanization, automation, and computerization applied to greenhouse production are discussed. Recent research activities conducted at Rutgers Univ. are presented for illustrative purposes.**

Agriculture encompasses human activities in managing and using biological resources to produce food, fiber, and ornamental plants to ensure a sustainable natural environment. It is a desirable component in a complete, independent society. Traditionally, production agriculture has involved laborious operations under conditions not conducive to human productivity. The advancement of technologies in other industries inevitably increases the threat of attracting labor away from agriculture. To maintain competitiveness, it is necessary to introduce technologies for modernizing agricultural production. Agriculture, in its modern form, should ideally be a well-balanced, energy-efficient system using state-of-the-art technologies resulting in high productivity. It fully uses human intelligence and mechanical power in a sustainable manner, while exerting acceptable impacts on humans and their environment. If agriculture is to prosper, its modernization must be a continuous process. Successful modernization will improve quality of living and working conditions. It also can provide job satisfaction, necessary for agriculture to be considered as a good choice of profession.

One aspect of agricultural modernization is development and application of methods that will increase labor productivity. Through the combined efforts of agricultural scientists and engineers, many agricultural operations in developed regions of the world have been highly mechanized, automated, and/or computerized. These operations have not only generated high outputs per unit of labor input, but also performed tasks beyond the physical capabilities of human labor. In many cases, the development of mechanization, automation, and computerization for agriculture starts with the identification and adaptation of technologies used in other industries. However, the variable characteristics and relatively low unit market prices of agricultural products frequently make direct adoption of existing technologies challenging, if not infeasible. In other words, technological feasibility and economic viability are very stringent criteria in the development of engineering systems for agriculture.

A greenhouse system is a form of production agriculture. This facility for commercial plant production within a controlled environment has recently become highly complex in its operation. Similar to other manufacturing factories, the design and operation of commercial greenhouses or plant fac-

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tories must emphasize the concept of a total systems approach. This requires expertise from engineering, horticulture, economics, and management. It is important to implement interdisciplinary cooperation in the system's integration for the successful realization of any controlled-environment plant-production system. In preparing his presentation for the Professional Plant Growers Assn. in Cincinnati, Reilly (1989) sent a questionnaire to several university professors and researchers. His objective was to identify recently developed technologies and understand driving forces for these developments. The most impressive implementations of new technologies were found in three areas: 1) energy conservation, 2) greenhouse productivity, and 3) labor productivity. Forces for change were mostly in reaction to overall economic changes and were external to the greenhouse. The energy situation, labor availability, government regulation, product demand, and technological development were mainly responsible for the development of these systems.

The greenhouse research group at Rutgers Univ. has been involved in developing engineering systems for greenhouses since the 1960s. The research on greenhouse mechanization, automation, and computerization for more-efficient production has been conducted under the areas of production environment, growing systems, operations research, flexible automation, and expert systems. In this article, the concepts of mechanization, automation, and computerization are discussed. Related research projects recently conducted at Rutgers Univ. for improving greenhouse efficiency and labor productivity are also presented.

Mechanization

Two major functions of agricultural mechanization are to substitute for human and animal physical power and to improve uniformity of operations (Garrett, 1985). In addition to labor shortages, a need for mechanical power may come from limitations of labor skill and capability, a harsh work environment, or management advantages. Quality control for product uniformity is beneficial in meeting market requirements. The ability to maintain uniform operations also enables predictable crop scheduling and production planning.

In mechanizing a given greenhouse task, engineering design principles and plant characteristics are considered. Technically, engineering design is a process of developing a workable system that performs assigned tasks and satisfies imposed constraints. In the greenhouse case, constraints include horticultural practices and scientific/engineering laws. Several approaches are commonly seen in designing mechanical systems to carry out greenhouse operations. Machines may be designed to work with the existing plant cultural practices by directly emulating human motions or creating different motions to accomplish the task. There are also cases where plant cultural practices are modified to facilitate the engineering design. Each approach has its own merit as long as a design for a specific task is compatible with the entire system under consideration.

Frequently, the solution to a mechanization project may consist of more than one workable design. The selection of the "best" design becomes the process of optimization. In this process, a criterion must be established and evaluated by using an objective function. The objective function is a relationship governing the criterion and the associated design parameters. An optimum design is the workable design that gives an optimum (normally, maximum or minimum) objective function value. The performance indicators of a workable system include the system's productivity, reliability, complexity, and safety. Furthermore, its economic viability is obviously a very important consideration for successful commercial application.

Automation

Automation adds the following machine capabilities to a mechanized system:

1) *Perception*. Understanding of its surroundings is of great importance to an automated system. Its capabilities for gathering, processing, and interpreting information are its basis for reaction. Sensors and data-collecting systems are common devices used for this purpose. In a greenhouse, environmental parameters, time and spatial coordinates, crop conditions, and labor status are frequently monitored.

2) *Reasoning*. Logical deduction and mathematical derivation give a system the power to reach a decision necessary to issue instructions to guide the system's operation. This automatic reasoning power normally resides in software packages executed on computers.

3) *Communication*. The complexity of commercial greenhouses continues to increase. Greenhouse automation must consider the integration of many components. Flow of information and the hierarchical order of commands must be directed carefully among all the components.

4) *Task planning*. Mechanical devices exist in a greenhouse for performing control functions and physical work. The most common type of physical work is materials handling. To effect the operation of these mechanical devices automatically, task planning is essential. A robotic system is a good example for illustrating the importance of task planning. The execution of an algorithm for greenhouse environmental control can be viewed as another type of task planning at work.

Automation may be designed to assume various levels of sophistication based on the situation. Two major categories of automation are fixed automation and flexible automation. Fixed automation systems are cost-effective for mass production of standard items (e.g., an automatic seeder in a plug production operation). Flexible automation offers the potential economic advantage of fixed automation while enabling response to varying make-to-order batch processes. Computers integrated with generic machine tools make automation systems flexible (e.g., a robotic plug transplanting workcell). The key feature of a flexible automation system is its ability to perform various tasks by changing mainly the software and requiring minimum hardware change.

Computerization

Two primary advantages of using computers for information processing are their vast memory and high calculating speed. Computers, therefore, are very effective when used to gather sensor signals, analyze data, generate status reports, provide decision support, and/or instruct machines to perform physical work. Thus, computerization is an important process in facilitating the evolution from mechanization, through fixed automation, to flexible automation.

Computerization inevitably involves the integration of electronic hardware and software algorithms. The advancement of microcomputers in recent years makes hardware selection a relatively easy task when compared to the acquisition of special-purpose software packages. This is especially true in the greenhouse industry. Consequently, efforts for developing computer software more suitable for greenhouse operations need to be made. A commercial greenhouse system normally consists of a number of interrelated components, such as the structure, the environment within the structure, the crop-growing facility, the materials-handling equipment, the environmental control apparatus, and strategies. To ensure component compatibility, systems-level information-processing devices are needed.

Procedural systems and heuristic systems are two computer programming paradigms of particular interest for developing information-processing algorithms for greenhouse operations. Procedural systems are most suitable for straightforward, deterministic information processing involving complex mathematical calculations. Statistical analysis of the effects of environmental conditions on plant growth is a good example of a procedural-programming paradigm. Heuristic systems are expected to solve problems at a performance level normally seen with human experts. The systems contain expert knowledge and the method of using the knowledge. These systems are most suitable for dealing with qualitative problems involving uncertainties. A computer program for solving diagnostic-type problems may be developed better following the heuristic paradigm. Some research work is currently being done on integrating both paradigms to form hybrid systems (Engel et al., 1990; Perry et al., 1990).

Research at Rutgers Univ.

The results of four research projects related to mechanization, automation, and computerization for greenhouse production are hereby summarized. These projects are part of the research effort on controlled-environment plant-production systems made by the greenhouse research group at Rutgers Univ.

Control of enhanced greenhouse environment. This project investigated an enhanced greenhouse environment governed by an automatic control strategy and its effects on plant production (Giacomelli et al., 1990; Ting et al., 1990a; Wu, 1991). The greenhouse was enriched by CO_2 and equipped with supplemental lights. A phase change materials (PCM) energy storage unit was incorporated in the greenhouse to regulate the energy requirements for greenhouse heating and cooling with minimum venting. The plant production system was a nutrient film technique (NFT) for producing lettuce hydroponically.

Although increased CO_2 concentrations will enhance plant growth over a range of light intensities, an increase in light level may magnify this effect. In greenhouse production systems, supplemental lights may be provided in conjunction with CO_2 enrichment. During bright, sunny hours, even in the winter of temperate climates, ventilation frequently is required to reduce the temperature in the greenhouses. The necessity of greenhouse cooling by ventilation may become a limiting factor for effective CO_2 enrichment, especially when additional heat is added by the supplemental lights. Therefore, some other means of cooling to minimize the venting requirement are needed to obtain the full benefit of accelerated plant growth in CO_2-enriched greenhouses. A PCM energy storage device has been studied for its potential use in regulating greenhouse temperature.

PCMs are capable of absorbing and releasing latent heat over a narrow temperature range. Glauber's salt ($Na_2SO_4 \cdot 10H_2O$), a popular PCM, has a melting temperature of ≈32C. This melting temperature may be lowered by adding sodium carbonate decahydrate ($Na_2CO_3 \cdot 10H_2O$) to form a eutectic mixture. The melting point of the PCM used in this study was ≈23C. This temperature was selected as suitable for the dual purpose of greenhouse daytime cooling and nighttime heating. The PCM was packaged in a tube-sheet form and hung in an air chamber. Every tube sheet was made by hot-bar sealing of two laminate films into pouches containing PCM.

The control strategy for monitoring and maintaining the greenhouse environment was programmed on a microcomputer using the commercially available software system GENESIS (Genesis Control Series, Iconics, Foxboro, Mass.). Controlled environmental parameters were greenhouse daytime and nighttime temperature ranges, CO_2 concentration, supplemental light, and nutrient solution flow. Environmental conditions were continuously measured by various sensors. The maintenance of these environmental parameters within the desired ranges was achieved by operating several electromechanical devices under instructions given by the control software. The devices were a ventilation fan, a supplemental heater, supplemental lights, a CO_2 supply, and a nutrient solution pump. Setpoint values of the controlled parameters could be changed easily through keyboard entry. More than ten 4-week lettuce crops were grown in this experimental facility. The automatic control system functioned well with minimum human supervision.

Decision support software for integrated greenhouse production system. Several decisions for the planning and operation of an integrated greenhouse system and the sophisticated design process are required (Ting et al., 1991). Appropriate information is essential for every successful decisionmaking process. It needs to come from various disciplines such as engineering, horticulture, operations research, computer science, and statistics. The greenhouse operator's practical knowledge, a result of many years experience, is particularly valuable.

A computerized decision support system has been developed to manipulate information useful for greenhouse planning, design, and operation. The activities of decision support are gathering, storing, retrieving, analyzing, presenting, and interpreting information to aid in the decision-making process. Results of a series of projects have been used as the building blocks of this decision support system. Software packages are available for engineering economic analysis (Ting et al., 1989), simulation of greenhouse internal transport (Fang et al., 1990a), resource allocation for greenhouse production (Fang et al., 1990b), and strategic planning of greenhouse production systems (Fang, 1989). All the software packages are modular, user-friendly, and menu-driven. Most of them can be executed on microcomputers without other commercial packages.

Single-truss tomato production system. The fundamental purpose of this production system is to produce continuously predictable quantities of tomatoes of uniform quality throughout the year (Janes and McAvoy, 1991). Economic viability is also a major consideration. Based on this criteria, research was performed in several areas to establish knowledge bases necessary for planning, designing, and operating the production system.

In a single-truss tomato production system, tomato plants are grown in a high population density on movable benches. The apical meristem of each plant is pruned above the first truss of flowers. Only the first cluster of fruits are allowed to develop for harvest. After harvest, the plant is discarded. A number of production blocks (crops) at various growing stages are grown simultaneously in a greenhouse. Supplemental lights are always required in the regions where natural light is a limiting factor. In some cases, CO_2 enrichment is used to promote photosynthesis. The advantages of this production technique include: 1) efficient materials handling, 2) efficient use of space, 3) efficient use of light, 4) predictable production scheduling, 5) high-quality fruits, 6) excellent potential for mechanization and automation, 7) high labor efficiency, 8) short cropping cycle, and 9) year-round production.

Some major research and development activities are presented in the following. McAvoy (1984) evaluated the growth of single-truss tomato plants under high plant density and supplemental lighting conditions. One-hundred-two plants were grown in 11.4-liter bags of a peat–vermiculite mix on a 1.73×5.1-m movable bench. High-pressure sodium (HPS) lights supplemented photosynthetically active radiation (PAR) at 125 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 18 h (04:00–22:00 HR) daily. Carbon dioxide was maintained at 1200 ppm during nonventing hours. The effect of light enhancement on the yield was significant over periods when natural light was limiting.

McAvoy et al. (1989) developed a plant factory model, including a regression-based plant-production model, for the single-truss tomato crops. The independent variable was total PAR received by the plants during the seedling stage (emergence to flowering) or the production stage (flowering to harvest). The dependent variables were the number of days of the seedling stage and fruit yield.

Giniger et al. (1988) developed a computer-simulation model using the crop-production model. It determined a production schedule for providing continuous yield, optimized greenhouse usage, and predicted production rates on a year-round basis.

Ting et al. (1989) developed an engineering economic analysis software package to analyze the economic viability of the cropping system. The software provided greenhouse engineers and managers a useful tool for justifying a particular investment. Cost of supplemental lighting vs. the increased tomato yield was investigated. They found that a moderate increase in tomato market price resulted in a significant increase in the overall rate of return on investment. The single-truss tomato cropping technique should produce fruits of higher market value than field-grown tomatoes.

Giacomelli et al. (1988) developed a procedure for improving uniform growth of tomato. Uniform development is an important factor in the single-truss tomato production system where plants are grown in a continuous batch fashion. It is highly desirable that all fruits in the same batch mature within a narrow time period, preferably <2 weeks. The selection of plants of uniform growth should be done as early as possible to conserve production resources. Their procedure allows growers to screen tomato plants at three stages: 1) root radical emergence, 2) the opening of the cotyledons, and 3) the first true leaf 25 mm in length. Machine-vision algorithms are being developed to automate this screening process (Ling et al., 1990).

Kabala and Giacomelli (1989) designed and tested a closed-loop transportation and elevation system for benches used in greenhouse crop production. For plant growth in a greenhouse, the benches were situated close to the floor to take advantage of floor heating and overhead supplemental lighting. However, for human worker comfort and efficiency, the benches needed to be elevated. Benches in the production area needed to be transported from one row to the other. Therefore, their system had a transfer-elevation device (TED) and two rear-transfer devices. Input and output of benches to and from any row within the greenhouse was possible. A bench elevation capability also was included.

Fischer et al. (1990) used the benching system developed by Kabala and Giacomelli (1989) on single-truss tomato production. Plants were grown in rockwool cubes on rockwool substrate and irrigated by the ebb–flood method. Every movable bench was sloped toward a corner where a siphon drain was located. They investigated the effects of 1) rockwool substrate (mats or slabs), 2) depth and duration of flood, and 3) plant position on a bench on the fruit weight and timing of harvest.

Luxhoj and Giacomelli (1990) compared labor standards for the single-truss tomato production system. Pruning and harvesting operation times were studied since they have a high frequency of occurrence. They identified a method for estimating operation times, which could enable the establishment of efficient labor management for greenhouse production.

Robotic workcell for plug transplanting. Flexible automation and robotics technologies have been developed to manipulate transplants in the form of plugs. Plugs are actively growing young plants with two well-defined morphological parts: the stem–leaf portion and the root–growth medium portion. Plugs may be grown from seeds or tissue-cultured materials in regularly situated cells on tray-like containers. The development of a robotic workcell to transplant plugs from the plug tray to a growing flat was one goal (Ting, 1990; Ting et al., 1990b). The workcell contains a four-axis SCARA robot, a sliding-needles with sensor end-effector, two overpassing conveyer belts for transporting plug trays and growing flats, and a designated location (dump point) for discarding rejected plugs.

In this workcell, the plug tray and the growing flats are loaded on the conveyer belts and brought to their working positions. The robot extracts one plug at a time from the tray and plants it into the growing flat. In the process of transplanting, a proximity sensor installed on the end-effector checks the presence of the plug to ensure that the growing flat will be filled with plugs when it leaves the workcell (Ting et al., 1990c). If the sensor fails to detect a plug after extraction, the end-effector will be moved by the robot to the dump point and action will be taken to clear any possible residue from the end-effector before attempting to extract the next plug. A systems analysis was performed to study factors affecting the workability and productivity of the workcell design. The factors included: 1) the dimensions and kinematics of the robot and its peripheral equipment, 2) the layout and materials flow through the workcell, and 3) the probabilities associated with misses in plug trays and successful extractions of plugs from the trays. A computer simulation program was developed to aid the systems analysis (Ting et al., 1990d). Stochastic modeling techniques were used to deal with probabilistic factors.

A software package for performing economic analyses of plug-transplanting robot workcells has been developed (Fang et al., 1991). It is capable of estimating payback years and return on investment for a given workcell design, making it very useful for conducting feasibility analysis, parametric analysis, and comparison of alternatives.

Conclusion

Mechanization, automation, and computerization are very important endeavors in modernizing greenhouse operations and maintaining market competitiveness. Activities may be classified into the following categories: 1) implementation of computer technology and instrumentation, 2) sensing of biological and environmental properties, 3) modeling biological processes, 4) automating expert knowledge (including informational, procedural, and heuristic), 5) engineering biological systems, 6) developing strategies for controlled-environment agriculture, and 7) flexible automation, robotics, and intelligent machines. Participation in these processes builds experience and knowledge bases. Outcome of these activities frequently ensures continuity of research and development capability.

Successful agricultural mechanization, automation, and computerization activities are normally characterized by the interdisciplinary approach, system-level thinking, thorough coordination and cooperation, good communication, public awareness/acceptance, industry support, and well-organized efforts in research, education, and extension. The implementation of these activities are influenced by 1) technical and labor effort; 2) past experience; 3) hardware and software facility; 4) managerial vision, structure, plan, and policy; 5) logistics; 6) morale; and 7) capital availability.

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