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BIOMECHATRONICS FOR AGRO-INDUSTRIAL APPLICATIONS

Haruhiko Murase

Graduate School of Agriculture and Biological Sciences,
Osaka Prefecture University, 1-1, Gakuen, Sakai 599-8531 Japan

Abstract: This article includes overviews of recently developed mechatronics, robotics, and precision technologies for plant (seedlings, flowers, fruits and vegetables) production and processing systems. Transplanting machines, grafting machines, and smart farm vehicles are discussed, and biorobots, such as those for cherry tomato, strawberry, and grape harvesting, are mentioned. Commercialized robotic systems for the production of chrysanthemum cuttings are highlighted in the robotic section. Precision agriculture, including microprecision systems for plant factories, is also discussed. *Copyright ©2000 IFAC*

Keywords: mechatronics, harvesting robots, precision agriculture, sensor-based technologies, plant factory

1. INTRODUCTION

The growing importance of mechatronics, a truly multi-disciplinary approach to engineering, is becoming increasingly apparent. New products and systems based on the integrated application of mechanical, electronic, and computer engineering technologies are demonstrating reduced mechanical complexity, increased performance, and often previously impossible capabilities. These advances have been stimulated by several factors, including developments in microprocessors, new and improved sensors and actuators, and novel software techniques. Biomechatronics is a new form of hi-tech mechanization in agricultural engineering that goes beyond conventional mechanization concepts. It is based on a synergy between the disciplines of agricultural machinery engineering and electronics involving instrumentation, control, and systems technology. Biorobotics is a category of biomechatronics that involves components such as a robot arm for the fine positioning of a tool or an end-effector for the specific tasks with which the action is performed. The terms biomechatronics and biorobotics are not yet clearly defined, even within professional communities. In this article, biomechatronics is defined as a discipline dealing with machine systems involving sensor systems, control systems, intelligence, and information technologies that can be implemented in bioproduction systems.

Although many bioproduction operations and processes have been mechanized, numerous tasks remain that are unsuited to human beings but require certain human-like intelligence. In the last decade, researchers and industry have developed prototypes of biomechatronic and biorobotic systems for use in bioproduction, many of which have been commercialized. For example, the transplanting machine, the grafting machine, the cutting sticking machine, and other hi-tech machines for bioproduction are commercially available. Harvesting robots, milking robots, and other biorobots have been commercially developed.

Reduction of the use of off-farm inputs with the greatest potential to harm the environment or the health of farmers and consumers has become a very important environmental issue. While low-input sustainable agriculture (LISA) has failed to gain appreciable support from the agricultural sector, since the nature of LISA decreases profits, the implementation of precision agriculture (PA) has been embraced. The development of precision technologies to reduce the use of off-farm inputs has been supported by the extensive application of information technology, such as GPS and GIS, and mechatronic technology, including sensor fusion and intelligent control. Microprecision agriculture has been proposed for the advent of greenhouse automation and plant factories.

This article includes overviews of recent developments in mechatronics, robotics, precision technologies, and sensor technologies for plant (seedlings, flowers, fruits and vegetables) production systems.

2. HI-TECH MACHINES FOR BIOPRODUCTION SYSTEMS

2.1 Transplanting machine

Mechanization in the floricultural industry is far behind that of other crop farming industries. Large-scale flower growers, who handle millions ofseedlings, believe that mechanization will become indispensable. Statistics show that 65% of Japanese flower growers want watering mechanized, and 45% of growers want machines for nursery soil preparation, filling soil in plug trays, and transplanting. Machines for watering, making soil, and filling soil have been more or less commercialized. Transplanting involves relocation of seedlings from smaller to larger plug trays according to the growth stage or size of the seedlings. Since the transplanting process is rather complex, most transplanting remains a manual operation. Most available commercial models of transplanting machines cannot recognize when plants are missing from a tray, forcing workers to replant poorly grown seedlings and fill missing seedling pots manually after the machine transplant operation.

One of the leading Japanese agricultural equipment companies has commercialized a transplanting machine that is capable of detecting missing seedlings. Only two sets of photoelectric sensors are required to detect the existence of seedlings, and poorly grown seedlings that should be removed can also be detected at a satisfactory level of accuracy (Yamada, 1999).

2.2 Grafting machine

Grafting is used for different purposes, such as growing crops using fewer agricultural chemicals or producing high quality produce such as bloomless cucumbers. Grafting has been practiced in Japan for about 70 years, to stabilize production by eliminating injury to the soil caused by successive cropping. About 90% of the watermelons, cucumbers and eggplants grown in greenhouses rely on this technology. In 1993, a grafting machine was commercialized in Japan (Kobayashi, *et al.*, 1999). The machine utilizes the CCG (cutting a cotyledon off grafting) method as an effective grafting mechanism for cucurbitaceous vegetables. The stock is prepared by cutting off one of the cotyledons together with the growing tip, and a scion is cut slant-wise at the hypocotyl. Another grafting machine that can handle not only cucubitaceous vegetables but also solanaceous vegetables has been developed with a new grafting technique, called the _plug-in method (Nishiura, *et al.*, 1995). The plug-in method was designed to perfectly join the vascular bundles of scion and stock (Fig. 1). A scion stem is shaped to form a plug shaped like a pencil-tip, using an ultrasonic vibration cutter, and a conical hole is drilled in the stock stem using a tapered drill. This grafting machine will be available on the market soon.

Fig. 1 Plug-in grafting machine.

2.3 Smart farm vehicle

An unmanned tilling tractor has been developed as an autonomous farm vehicle. The tractor is equipped with sensors such as an off-the-wire electromagnetic induction-type vibro gyroscope, a GDPS inertial navigation device with a geomagnetic direction sensor, and an optical auto-tracking traverse with a geomagnetic direction sensor. The tractor can learn tasks; instruction is provided by an operator at the beginning of the operation, and the training process requires 2 to 5 min (Yukumoto and Matsuo, 1995).

An automonous vehicle for greenhouse use has been also developed. The vehicle travels in the space between rows or cultivation beds in a greenhouse. The vehicle is equipped with ultrasonic and proximity sensors (Yamashita and Sato, *1999*).

3. BIOROBOTICS

There have been many applications of robotic technologies to agricultural operations, such as harvesting, planting, spraying, grafting, milking, bagging, weeding, fertilizing, tilling, etc. Research into fruit-harvesting robots started 15 years ago in Japan, and more research has been devoted to fruit-harvesting robots than to any other type of agricultural robot. In the USA, Europe, and Israel, several harvesting robots have been reported; fruit-harvesting robots with manipulators are entering the final stage before commercialization by agricultural machinery companies (Kondo and Ting, 1998)..

There are many problems to solve when developing agricultural robots. The work objects for agricultural robots have various physical properties, such as size, color, shape, hardness, texture, etc., even when the robot operates on the same variety of plant. In addition, the robots are required to work in various environmental conditions. Not only is air temperature and humidity of concern, but illumination and light color also change temporally and spatially. Therefore, the robots must recognize and understand the physical properties of objects, be able to work in various environmental conditions in fields or greenhouses, and be robust enough to withstand the problems caused by water and dust. Plant training systems and cultivation methods have been changed so that the productivity and quality of the fruit can be improved and farmers can work easily.

The following sections describe basic components of fruit-harvesting robots, especially manipulators, end-effectors, and visual sensors adapted to the physical properties of biological objects, by introducing tomato-, cherry tomato-, strawberry-, and grape-harvesting robots.

3.1. Biological object

Tomato plant. The phyllotaxis of most tomatoes cultivated for the fresh market in Japan is so methodical that all flower clusters emerge in the same direction. Therefore, tomatoes are transplanted so that the clusters are directed to the aisle side of the ridge, and grown vertically with supports until all of the fruits of the sixth cluster have been harvested. The position of fruit is one of the important factors when considering the mechanism of a manipulator.

In many varieties of tomatoes, a cluster usually has several fruits and the peduncle has a joint. The fruits in a cluster are adjacent to one another, but they do not ripen at the same time. It is therefore necessary to harvest only the ripe fruits, without injuring other fruits, leaves or the stems of the plants. When a farmer harvests ripe fruits manually, he can easily pick them by bending the joints instead of cutting the peduncle.

Cherry tomato plant. Cherry tomato plants are usually grown in a greenhouse, and have multiple fruit clusters. Their phytology is almost identical to that of larger tomatoes, so that all of the flower clusters emerge in the same direction. However, stems are sometimes twisted, and part of the fruit cluster is often hidden by leaves and stems. The fruit clusters each consist of approximately two dozen fruits, and the peduncles of the fruits have a joint in many varieties of cherry tomato plants. When the fruits are harvested manually, they can be picked by nipping the joints. A cherry tomato plant has small fruits 20-30 mm in diameter, which do not become ripe simultaneously; ripe fruit is therefore harvested selectively. However, harvesting is labor-intensive because of the large number of fruits.

Strawberry plant. Strawberries have traditionally been grown on ground covered with plastic, although the use of hydroponic systems for strawberry production using tabletop culture has been increasing recently. This strawberry training system is very suitable for robotic operation: the fruit hangs down from the hydroponic bench and vertical growth is small; there are few obstacles around the fruit; peduncle length can be chemically controlled for a wide range, and the fruit is easily transported after harvesting because of its small size. The characteristics of the strawberry plant are ideal for robotic harvesting, except for the fruit's delicate surface.

Grapevine. Grapevines grow on trellis training systems in Japan. The height from the ground to the trellis is about 170-190 cm to allow people to move under the trellis easily. Grape bunches are harvested when the fruit changes color and the sugar content becomes sufficiently high. The sugar content is measured manually, using a device, by squeezing several sample fruits picked from bunches. All of the bunches in an orchard are often harvested at the same time, once the sugar content is high enough.

3.2. Manipulators

Tomato and cherry tomato harvesting. The basic mechanism of a manipulator depends on the configuration of the plant and the 3-D positions of its work objects. A five DOF articulated manipulator was used for the first attempts to robotize the tomato-harvesting operation. However, the mechanism of the manipulator was unsuitable because only the operational space was considered, and even when the fruit was in the operational space it did not work efficiently,. Therefore, a 7 DOF manipulator has been developed for traditional tomato plant training systems.

Strawberry harvesting. In tabletop culture of strawberry plants, a five DOF polar coordinate manipulator can be used for the robot harvester, because obstacles are rare in tabletop cultures. This manipulator moves under the table.

Grape harvesting. Another five-DOF polar-coordinate manipulator was applied for this training system, assuming that the robot traveled along the main scaffold. Since there are few obstacles under the trellis, the mechanism of the manipulator includes a prismatic joint, so that the manipulator can work quickly using a simple control method. The joints are controlled at various speeds by using DC servo motors that allow the manipulator end to move horizontally below the trellis. The length of the arm is 1.6 m, and the stroke is 1 m.

3.3. End-effectors

Tomato harvesting. A two-fingered hand with a suction pad has been developed for tomato harvesting. The gripping force exerted by the finger plates can be adjusted from 0 to 33.3 N. These finger plates grip fruits ranging from 50 to 90 mm in diameter. The suction pad is attached to the end of a rack that is driven back and forth by a DC motor and a pinion located between the finger plates. The speed and the stroke of the suction pad motion are 38 mm/s and 80 mm, respectively. The pad can be moved forward up to 43 mm from the tips of the finger plates. The distance moved and stopping position of the pad can be detected by a rotary-type potentiometer.

The motion of the end-effector is as follows. The manipulator moves the end-effector to an appropriate position near a target fruit and the suction pad moves toward the fruit. The pressure and position of the suction pad are constantly monitored. As soon as the pressure on the pad reaches a predetermined set value, the pad stops, the vacuum pump is turned off, and the pad begins to move backwards. This pad motion was designed to isolate the target fruit from others in the same cluster. Once the pressure in the pad reaches another set value, the finger plates simultaneously start to move toward the fruit at the same speed as the suction pad. This enables the fruit to remain at a constant absolute position. Finally, the finger plates grip the fruit and the end-effector harvests the fruit by bending it at the peduncle. The fruit is then released into a tray.

Cherry tomato harvesting. The fruit is pulled into the end-effector, which pneumatically sucks the fruit provided that it is positioned within a 40-mm radius of the center of the end-effector in the tube opening (Kondo, *et al.*, 1996). The design of the end-effector helps to relax the accuracy requirement for the vision-based positioning action. Three pairs of photo-sensors detect the fruit location in the end-effector. If the fruit is at an appropriate position, its peduncle is nipped near the joint by the action of a nipper closing. The nipper is actuated by two springs and a solenoid. Once detached from its peduncle, the fruit is transported through the tube to a holding container by suction.

Strawberry harvesting. An end-effector for strawberry harvesting is under research (Satou, *et al.*, 1996). The principle is similar to that for cherry tomato harvesting.. Fruit is pneumatically sucked into the end-effector. Three pairs of photo-interrupters detect the position of the fruit in the end-effector. When the fruit is in an appropriate position, the wrist joint rolls, and the fruit's peduncle is then cut using a cutter driven by a solenoid actuator and springs.

Grape harvesting. In addition to the functions of grasping and cutting the rachis, the ability to push a grape bunch was incorporated in the end-effector. This enables the end-effector to grasp a very short rachis at harvest time, reduces any swinging of the bunch during transport after harvesting, and orients the bunch during its release. The cutter and finger are driven by a DC motor and two springs. The pushing device moves in a straight line using another DC motor and a rack and pinion (Kondo, 1991).

Cucumber Harvesting. Cucumbers must be harvested daily because they mature rapidly and their quality deteriorates if they are harvested too late. A cucumber-harvesting robot uses a visual sensor, manipulator, end-effector, and traveling device. This robot has also been commercialized. To discriminate cucumbers from leaves and stems, a monochrome TV camera with 550-nm and 850-nm wavelength interference filters is used. After thresholding the images, cucumbers are recognized morphologically. A polar coordinate manipulator with seven degree of freedom moves to a target cucumber, and the harvesting end-effector grasps the top, detects the peduncle, and cuts it. The manipulator and end-effector were trial-manufactured based on the cucumber's physical properties. The robot is moved from plant to plant on a 4-wheel traveling device (Arima and Kondo, 1999).

Chrysanthemum Cutting Sticking Robot System. The cutting sticking operation is essential for chrysanthemum production to enhance productivity. Since several hundred million chrysanthemum seedlings are produced each year in Japan, much time and labor are required to perform the sticking operation. Automation of this monotonous task was desired. A robotic cutting sticking system mainly consists of four sections: a cutting-providing system, a machine-vision system, a leaf-removing device, and a sticking device. First, a bundle of cuttings are put into a water tank. The cuttings are spread out on the water by the vibration of the tank. A TV camera supplies information on the positions of the cuttings, which are selected by a manipulator and sent to the next stage one by one. Another TV camera detects the position and orientation of the transported cuttings, and indicates a grasping point on the cutting stem for another manipulator. The manipulator moves the cuttings through a leaf-removing device that removes the lower leaves to a sticking device. Finally, 10 cuttings at a time are stuck into a tray. This system has been commercialized (Kondo and Monta, 1999).

Other biorobots. Mushrooms are typically grown under structures in a composted mixture of straw and animal manure. Most are harvested by hand for the fresh market. An attempt has been made by the Silsoe Research Institute in the UK to mechanize the harvesting operation using a robot (Reed, et al., 1995). Milking robots are another successful example of biorobotics (Hachiya, et al., 1996; Hayashi, 1999; Hogewerf, et al., 1992; Kuipers, 1996). The traditional milking machine provides teat cups that milk by suction pressure; attaching the teat cups to the cow used to be done by human hands, but the milking robot attaches the teat cups automatically. Many years ago, wool-shearing robots were developed at the University of Western Australia to reduce the cost of wool harvesting (Australian Wool Corporation, 1988). The sheep were held on trolleys, and were automatically moved to one of the shearing stations. The robot's computer was programmed with a generalized map of the shape of a sheep's surface. The robot used this blueprint to move the cutter close enough to the skin for the sensors to detect and navigate the surface.

4. PRECISION TECHNOLOGIES

4.1 Two methods of precision agriculture

Map-based technologies. Currently, the majority of available technologies and applications in precision agriculture utilize map-based methods of pre-sampling, map generation, and variable-rate application. The map-based approach is the most popular because of a lack of adequate sensors for monitoring soil conditions, and laboratory analysis is still the trusted and reliable method for determining most soil properties. However, the cost of soil testing limits the number of samples that a farmer can afford to have tested. Thus, the usual practice is to grid sample a field every 2 acres. (There is currently much discussion on the optimum number of acres represented by each sample and the best location of those samples.)

Detailed mapping of fields is easily performed using a computer program, sometimes with a geographical information system (GIS) program. Some programs can use algorithms for _smoothing_ or interpolating the data between sampling points, while others use a constant value for the measured property over the entire area, e.g., 1 hectare. In either case, such mapping facilitates long term planning and analysis. It provides an opportunity to make decisions regarding the selection and purchase of seed and chemicals well in advance of their use.

Maps are especially good for collecting data for variables that do not fluctuate from season to season. Variables such as organic matter, soil texture, and possibly yield potential, change slowly, if at all. Soil fertility with regard to particular nutrients, such as phosphorous and potassium, may change from year to year, but benefits can still be obtained by sampling every 2 to 3 years. Other nutrients, such as nitrogen, may vary considerably, even during one growing season, and therefore require measurement and mapping every year.

These computer-generated maps have to be converted to a form that can be used by a variable-rate applicator. The applicator's controller then calculates the amount of chemical to apply at each moment. Again, a DGPS system must be used to continuously correlate the location of the applicator in the field with a coordinate on the map and the desired application rate for that coordinate. Most variable-rate controllers attempt to synchronize the application rate with the position in the field by looking ahead_ on the map for the next change in rate. This takes into account the time required to adjust the rate coming out of the applicator and the ground speed of the tractor.

The width and the controllability of the applicator along its width is another issue related to the required resolution of maps in precision agriculture. If a spray boom is 60 feet wide and each nozzle cannot be controlled independently, then the usefulness of variable-rate application may be limited. However, if each nozzle is controlled independently, then the resolution of the map used to control the spray must be very good.

One benefit of the map-based method is a priori knowledge of the required amounts of chemicals, or inputs, for the operations. For example, a farmer knows exactly how much fertilizer he will need before he even enters the field (similar to when constant-rate application is used).

Sensor-based technologies. Technology is becoming available that utilizes a method that can be described as real-time sensing and variable-rate control. Crop Technology, Inc., Houston, TX, markets one such system. Their system, the Soil DoctorR, claims to examine soil type, organic matter, cation exchange capacity, soil moisture and nitrate nitrogen levels using a rolling electrode. By sensing these properties on-the-go, the need for a positioning system is eliminated, and because no maps are required the data processing is greatly reduced. However, if the operator wishes to record the sensor outputs and use this information for other operations, the system is capable of interfacing with a GPS to generate site-specific maps.

This type of system also has a problem with synchronizing the sensor measurements with the desired application rate for a given site. In some instances, the sensor may have to be mounted in front of the tractor, or spreader truck, to give the variable-rate applicator's controller sufficient time to adjust the rate accordingly before it passes the sensed location. In order to effectively accomplish this real-time control, the sensors must respond almost instantaneously to changes in the soil. For example, a bulk fertilizer spreader truck may operate at field speeds of 40 kilometers per hour. This means that more than 100 m pass beneath the truck if the lag time of the system is one second.

A soil organic matter sensor has been developed at Purdue University for this purpose. Currently, Tyler, Benson, MN, has licensed this sensor, to vary rates of application of dry soil-applied herbicides and/or blended fertilizer on-the-go without a map. The organic-matter sensor consists of a photodiode surrounded by six light-emitting diodes (LED's). The LED's shine red light onto the soil surface and the photodiode measures the amount of reflection, which is related to the amount of organic matter in the soil. Moisture can affect the sensor, but provided that the soil is moist, the effects are small.

Other researchers are actively developing sensors for real-time measurement of nitrate nitrogen (in soils and animal waste), soil pH, potassium and phosphorous and soil texture. If these efforts succeed, site-specific farming will become more economical, and possibly even automated.

4.2 Latest advances in soil-sensor technology

Using spectral-based techniques, a spectrophotometer for collecting the visible to near-infrared spectral reflectance of underground soil at depths of around 30 cm has been developed. The proposed sensor system is composed of a soil-penetrator with micro optical devices to collect the soil reflectance, a spectrometer to detect the spectra of reflected light between 400 and 1700 nm, and a control and data-logging device consisting of a personal computer and a pulse generator. The soil sensor was mounted to a 4WD 18kW tractor with a three-point hitch. Clear photo-spectral reflectance was obtained from the underground soil at depths of 28 cm, at intervals of 23 cm. In laboratory tests, the soil reflectance was equal to that obtained by desktop spectrophotometers.

Shibusawa (1999) has developed an on-line real time sensing system using a spectro-photometer for soil fertility detection.(Fig. 2). The sensor system is composed of three main sub-systems. The first is a soil-penetrating chisel with a housing for micro optical devices. The chisel tip creates a cylindrical hole, and then a soil-flattening blade reshapes the flat-bottom to give the uniform surface texture required for diffusive light reflection. In the housing, the two optical fiber probes used for illumination are angled so that their centerlines cross at a depth of 75 mm. This gives an illuminated area more than 30 mm in diameter. Another two optical-fiber probes are used to collect the soil reflectance of the respective visible and NIR ranges over the 30-mm diameter area at 75-mm depth. These optical fibers are able to pass light over wavelengths between 400 and 2400 nm. A micro CCD camera (Toshiba IK-UM42) is focused at 75-mm to monitor the exposed soil at that depth. The housing is about 600 mm long, 200 mm high and 50 mm thick, and is attached to a 700-mm deep, 100-mm wide and 25-mm thick shank. A micro NIR thermometer is also installed to monitor variation in soil temperature. It was confirmed that depths greater than 20 cm provided the degree of darkness required for measuring soil reflectance without disturbance from solar radiation.

Fig. 2. Implement of soil spectrophotometer.

The second sub-system is an optical unit that consists of an illumination supply and a spectrometer. A

150-W halogen lamp is used, which provides light with a wavelength ranging from 400 to 2400 nm. The spectrometer has 256 channels of linearly arrayed photo-diodes (Carl Zeiss Ltd.) for 400 to 900 nm visible light, and 128 channels for 900 to 1700 nm NIR light. The minimum exposure time is 4 ms for the visible diodes and 1 ms for the NIR diodes. The data scanning time is therefore more than 4 ms. Integration of scanned data is carried out for each measurement in order to obtain averages at respective spectrums.

The third sub-system is a control and data logging system. A personal computer (233MHz, 128 MB RAM) with a liquid-crystal display controls the spectrometer, stores the collected data, and simultaneously exhibits the spectral reflectance of visible- and NIR-range light. A pulse generator consisting of a freely rotating wheel with a rotary encoder generates trigger timing signals with a resolution of 1.57 mm/pulse. The video monitor also displays the soil bottom images.

4.3 Variable-rate technology

Central to precision agriculture is a geographic information system that will enable knowledge-based farming decisions to optimize net profit. An important aspect of the technology is the ability to vary the rate of application of all inputs; that is, to tailor or prescribe application to various sites throughout each field, including tillage, fertilizer and lime application, planting, cultivation, and spraying. The components usually found in variable-rate application equipment have been outlined and discussed in some detail. The appendix contains two summary tables that provide information on most of the companies involved in producing variable-rate application equipment.

Most of the commercial ventures to date have focused on variable-rate equipment to apply liquid and granular materials. Many questions remain as to how best to implement this technology. GIS is the brain of the system, but this aspect of the technology is still in its infancy. A critical aspect of the new electronic technologies is standardization, ranging from physical connections able to withstand the farming environment, to the format of the collected data. It is critical that the methods and tools developed are simple to use, user friendly, and economical. Much more technical development remains to be done before the precision farming systems of the future can be implemented. In the final analysis, it must be shown that precision farming pays economically, environmentally, and from the viewpoint of the conservation of our natural resources.

4.4 Microprecision technology

The open field agricultural system is a typical example of a large-scale complex system. It has been attracting the attention of researchers and scientists in various scientific and engineering fields. PA has become a promising practice, able to handle complex systems, with significant support from both the agricultural and industrial sectors. Although a plant factory is also a large complex system, it is much less complex than an open field system. There are quite a few plant factories operating commercially in Japan. PA is nothing but integrated technology, designed to optimize the cultivation process. The fully controlled environment of a plant factory can be considered an ideal cultivation system in terms of alternative agriculture. Most of the environmental factors in a fully controlled plant factory are observable and controllable; a plant factory can be optimized more easily than an open field. Microprecision agriculture for a fully controlled plant factory is proposed in this paper. Microprecision agriculture can be attained by using plant factories to realize profitable alternative agriculture (Murase, 2000).

Development of plant factories. More than 50 years ago, a laboratory test using a phytotron revealed the remarkably positive effect of temperature optimization on tomato growth. In 1970, a plant growth system consisting of systematically integrated growth chambers was used to demonstrate that plant growth can be significantly improved by providing optimum conditions in terms of environmental factors such as temperature, humidity, light-intensity, and CO2-gas concentration. Those scientific achievements motivated the early development of closed plant-growing systems with a controlled artificial environment. This research and development led to the development of plant factories, which involve technologies such as process controls for the plant growth environment, mechanization for material handling, system controls for production, and computer applications. The advantages of a plant factory include production stabilization, more efficient production, better management of the quality of the product through a shortened growing period, better conditions, lower labor requirements, and easier application of industrial concepts.

A precise definition of a plant factory has yet to be established. In a broad sense, a plant factory is defined as a production system in which plants are under continuous production control throughout the growth period until the harvest. A narrow definition is an all-year-round plant cultivation system in a completely artificial environment_. There are many commercially operating greenhouse-type plant factories that are heavily equipped with sophisticated environment control systems, machines, instrumentation, and computers. Some use only natural light, while others use artificial light occasionally as a supplement during seasons of low solar radiation. Greenhouse-type plant factories are not the ideal system, because of the external disturbances that are unavoidable, unpredictable, and uncontrollable. However, such greenhouse-type plant factories have been more accepted by growers, mainly because of current energy costs and the high initial investment required for a fully controlled plant factory.

A closed, fully controlled, plant-growing factory is far better in terms of minimizing all sorts of waste. The limit and optimum design concept has to be applied to establish an economically feasible, fully controlled, plant-growing factory. To achieve this objective, microprecision technologies have to be developed. Microprecision does not necessarily mean a higher order of engineering precision. Microprecision in agriculture is the technological means to identify what and how much is needed to fulfill an identified quantitative and qualitative need as precisely as possible. Microprecision technologies should be involved in sensing, modeling, controlling, and collecting information for the mechatronics for plant production. Basic technologies for microprecision are already available; they are SPA (speaking plant approach to environmental control), AI (artificial intelligence: expert systems, neural networks, genetic algorithms, photosynthetic algorithms etc.), bioinstrumentation, non-invasive measurement, biomechatronics, and biorobotics (Hashimoto and Nonami, 1992).

Microprecision irrigation system. A microprecision irrigation system for plug production is an example of a microprecision technology that has actually been implemented in a plug seedling production factory. This is a kind of variable-rate technology in precision agriculture. The traditional irrigation method for plug production is an overhead watering system that provides an excess amount of nutrient solution to growing plug seedlings. In the traditional system, some of the nutrient solution used for irrigation is absorbed by the substrate (soil) and then by the plant, some remains on the surface of leaves, and the rest goes on the ground and is wasted. This has been a major drawback of the traditional irrigation method in plug production, from both an economic and environmental viewpoint.

Irrigation concept. Irrigation should be performed only on a seedling that requires water (nutrient solution). The proper amount of solution should be supplied for the particular plant at the proper location where the roots have developed. This concept assures the minimum amount of wasted irrigation water, with no residual of the solution over the leaf surface. Recycling of the nutrient solution does not need to be considered, since there is no overflow of nutrient solution. The water (nutrient solution) should be supplied from the bottom of the cell.

Design concept. The nutrient solution should be injected directly into substrate (soil) where the roots have developed, so that the leaves are not wetted by the irrigating solution. The nozzle for water injection should be inserted from the bottom of the plug cell. The cells must have an appropriate-sized hole at the bottom. The injection process should be completed as quickly as possible, since a very large number of seedlings has to be irrigated. Leaks of the solution from the cell during and immediately after the injection should be minimized or avoided.

Irrigation device. A microprecision irrigation device has been developed (Fig. 3). The device was designed to fit a 300-mm x 600-mm cell tray with 72 cells. The solution is discharged from 72 nozzles, which are fixed on an aluminum plate that can be moved up and down, and is actuated by a ball screw connected to a servo motor. The motor eventually controls the vertical position of the injection nozzle tip relative to the interior of a plug cell filled with substrate (soil mass) and roots. A solenoid valve connected to the nozzle meters the amount of solution discharged from each nozzle. The seventy-two solenoid valves are controlled individually so that the amount of solution discharged from each nozzle can be varied as required. This is one of the variable-rate technologies that are often highlighted in precision agriculture.

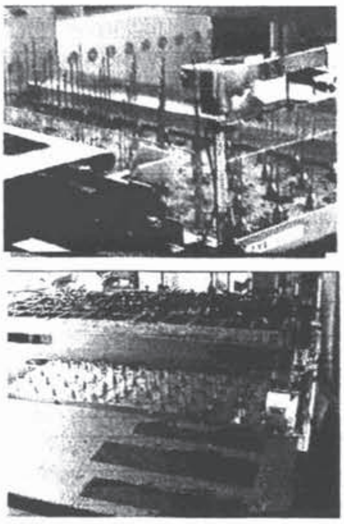

Fig. 3. Irrigation device

Irrigation system. The irrigation device is mounted on a multi-functional shifter that can both position a cell tray on an irrigation device and weigh each tray before and after irrigation to monitor the amount of water used or evaporated (Fig. 4). The cell trays are placed vertically in two-dimensional arrays. The irrigation unit can transport the irrigation device to cell trays that require irrigation. A computer controls irrigation scheduling and operation.

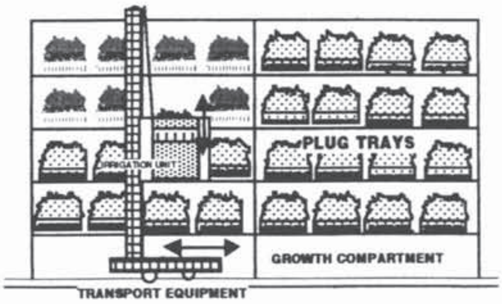

Fig.4. Microprecision irrigation system.

5. CONCLUDING REMARKS

Biomechatronics differs from mechatronics in manufacturing industry, mainly because of the need to combine engineering technologies with agricultural/horticultural technologies. Biomechatronics, including biorobotics and horticultural or agricultural technologies, is now progressing rapidly. Engineers and biologists should work closely together in the development of biomechatronics. Economic considerations are also an important aspect of the development of biomechatronics and biorobotics. There have been many research and development projects for hi-tech agricultural machines with impressive results; however, the utilization of such hi-tech machines is still limited compared to the use of automation in manufacturing industry. The development of biomechatronics and biorobotics presents some interesting challenges and exciting opportunities.

Although the IFAC has been promoting bioproduction robot research, this field is still considered emerging. It is not unusual to see extreme views expressed concerning the need for and direction of bioproduction robot development. Potential users in the bioproduction industry have mixed expectations for this kind of robotics technology. There is no doubt that robots have played an important role in improving productivity in many manufacturing processes, and application of robotics to bioproduction should not be unconditionally accepted or rejected. It is therefore important to discuss expectations for bioproduction robots in the future. The IFAC is considering this important aspect, as well as promotion of this research.

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