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Robotics for Plant Production

NAOSHI KONDO[1] and K.C. TING[2,*]
[1]*Agricultural Engineering Dept., Faculty of Agriculture, Okayama University, 1-1-1, Tsushima-Naka, Okayama, Japan, E-mail: nkondo@ccews2.cc.okayama-u.ac.jp;*
[2] *Dept. of Bioresource Engineering, Rutgers University-Cook College, P.O.Box 231, New Brunswick, New Jersey 08903-0231, USA, E-mail: ting@bioresource.rutgers.edu, Tel: (732) 932-9753, Fax: (732) 932-7931 (* Author for correspondance)*

Abstract. Applying robotics in plant production requires the integration of robot capabilities, plant culture, and the work environment. Commercial plant production requires certain cultural practices to be performed on the plants under certain environmental conditions. Some of the environmental conditions are mostly natural and some are modified or controlled. In many cases, the required cultural practices dictate the layout and materials flow of the production system. Both the cultural and environmental factors significantly affect when, where and how the plants are manipulated. Several cultural practices are commonly known in the plant production industry. The ones which have been the subject of robotics research include division and transfer of plant materials in micropropagation, transplanting of seedlings, sticking of cuttings, grafting, pruning, and harvesting of fruit and vegetables. The plants are expected to change their shape and size during growth and development. Robotics technology includes many sub-topics including the manipulator mechanism and its control, end-effector design, sensing techniques, mobility, and workcell development. The robots which are to be used for performing plant cultural tasks must recognize and understand the physical properties of each unique object and must be able to work under various environmental conditions in fields or controlled environments. This article will present some considerations and examples of robotics development for plant production followed by a description of the key components of plant production robots. A case study on developing a harvesting robot for an up-side-down single truss tomato production system will also be described.

Key words: automation, end-effector, manipulator, plant cultural practice, robotics, traveling device, visual sensor

Introduction

Robots have been playing an important role in automated materials handling in the manufacturing industry. Service robots have also gained attention in recent years. For agricultural production, robotics has been an active research topic in several parts of the world for more than 15 years. A substantial amount of effort in agricultural robotics development is aimed at improving automation in operations related to the production of plants. Robotics technology includes many sub-topics including the manipulator mechanism and its control, end-effector design, sensing techniques, mobility, and workcell development. Economic issues and the man-machine interface are also important.

Plant production occurs at many levels, ranging from micropropagation for plant regeneration to large-scale production of field crops and forest trees. In current commercial plant production systems, plant materials are frequently handled in large quantities. The need to use machinery in plant production to reduce human labor requirements, expand production capabilities, and improve uniformity of products has long been recognized. The mechanization of plant production enables a small percentage of the population who are modern farmers to produce large quantity of food, fiber, and ornamentals on a desired schedule. Owing to the biological characteristics of plants, they need to be manipulated in special ways, and sometimes with individual care. The cost of materials handling by manual labor and the availability of skilled personnel have become an increasing concern for plant producers. The advent of computers brought about the possibility of equipping machines with a certain degree of intelligence. A robot is a programmable intelligent machine equipped with sensing devices and changeable end-effectors, positioned and oriented by a mechanism, for performing multiple materials handling tasks. In addition to mechanization functions, robots also provide various automation capabilities with flexibility, which can be of great value to plant production operations.

In a broad sense, automation encompasses machine capabilities of information processing and task execution to facilitate a system's operation. Information processing includes the activities of information acquisition, organization, manipulation, interpretation, understanding, adoption, and presentation. Commonly applied information processing functions in an automated system are perception, reasoning, learning, and communication (Ting and Giacomelli 1992; Miles 1994). Task execution requires task planning and mechanical work. As mentioned above, robotics is an integration of computer technologies, sensing and control techniques, and generic mechanisms. The result is a flexibly automated mechatronic system well suited for performing, with some intelligence, various materials handling operations. Robots are normally working in concert with other sensing and materials handling devices within a defined space, e.g. workcell. The types of devices included in a workcell determines its overall functionality. Therefore, it is advisable to give careful considerations at the systems level before the actual implementation of the workcell design.

Applying robotics in plant production requires the integration of robot capabilities, plant culture, and the work environment. This article will present some considerations and examples of robotics development for plant production followed by a description of the key components of plant production robots: manipulator, end-effector, visual sensor, and travelling device. A case study on developing a harvesting robot for an up-side-down single truss tomato production system will also be described. Since most of the work on robotics for plant production to date is for horticultural crops, the emphasis of this article will therefore be on horticultural robots.

Horticultural Robots

Robots in manufacturing industries have become popular and have been studied extensively. Most used in factories usually consist of a manipulator and end-effector and can work under feedback or sequential control. Their work objects have certain, generally well defined, sizes, shapes, color, hardness, and texture. The work environments for industrial robots are mostly well structured regarding the lighting, layout, and materials handling procedures.

Commercial plant production requires certain cultural practices to be performed on the plants under certain environmental conditions. Some of the environmental conditions are mostly natural and some are modified or controlled. In many cases, the required cultural practices dictate the layout and materials flow of the production system. Both the cultural and environmental factors significantly affect when, where and how the plants are manipulated. In addition, the plants are expected to change their shape and size during growth and development. Individual plants within any given population will have significant variation in properties important to the robotic operation to be performed. The robots which are to be used for performing plant cultural tasks must recognize and understand the physical properties of each unique object and must be able to work under various environmental conditions in fields or controlled environments. They often need, therefore, sensing systems which can work under the variable conditions as well as specialized manipulators and end-effectors. The environmental conditions are occasionally so severe with regard to high temperature, humidity, dust and/or rain that electrical circuit and material corrosion problems can be major concerns. These conditions must be taken into consideration when designing or selecting plant production robot systems. In addition, when the work object is not easily positioned in front of the robot, a travelling device is required.

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Kozai et al. (1991) described the special characteristics of micropropagation procedures and the considerations for automation. A number of robotic based systems for multiplication of plant tissues and transplanting of plantlets developed by commercial companies and research institutions have been introduced. Okamoto et al. (1992) developed a tissue proliferation robot for dividing and transferring callus. A special end-effector equipped with a disinfected pair of razor blades and a suction pipe was carried by an articulated robot to perform the task. The robot was guided by a machine vision system in locating plant tissues on a petri dish. The average cycle time for dividing and transfer a callus was approximately 40 seconds.

There have been a series of projects in developing robotic systems for transplanting seedling plugs and cuttings. Transplants are used in both greenhouse and field production of floral and vegetable crops because of their many advantages including uniformity, earliness, etc. The additional labor required in handling transplants, as opposed to direct seeding, is the transplanting operation. Kutz et al. (1987), Ting et al. (1990), Yang et al. (1991), Tai et al. (1994), and Bar et al. (1996) have done work in using robots for transplanting plugs. Simonton (1990) developed a robotic workcell for geranium stock processing. Geranium cuttings were processed using this system for vegetative propagation. A grafting robot was developed by Suzuki et al. (1993) for preparing cucumber seedlings. The grafting operation involved the preparation of scions and fixing/adhering the scions on stocks. It was reported that the cycle time for producing a grafted seedling was about 3 seconds. Yamada et al. (1995) also developed a fully automated robot-based grafting robot.

Sevila (1985) studied an alternative grape vine pruning method to facilitate robotic applications. The new pruning method was evaluated and revised by a computer model and a laboratory scale robotic system was constructed. The system consisted of a cutting saw attached to a cutting arm, an image acquisition system, and an electronic controller. It was concluded that the method was physiologically and agronomically feasible. The robotic system was found workable with the new pruning method. At Cornell University, researchers have worked on the development of a robotic grape pruner. A computer model of a vision guided pruner was develped by Ochs and Gunkel to study the effects of the robot components and the variation of vine and terrain on the pruning accuracy (Ochs and Gunkel 1993). The design of a digital regulator and tracking controller for a robotic electro-hydraulic pruner was discussed by Lee et al. (1994). In related research, work has been done at Okayama University to develop a robot which would perform a number of operations in vineyard (Monta et al. 1994). The operations that the robot was capable of doing included spraying, bagging, berry thinning, and harvesting.

Harvesting of fruit and vegetables using robots has been a popular subject of research and development. Research works have been reported since

1983 on harvesting a variety of crops using robotic systems. The types of fruit and vegetables harvested included apple (d'Esnon 1985; Bourely et al, 1991), orange (Coppock 1983; Slaughter and Harrell 1987), peach (Vassura 1991), melon (Edan et al. 1994), watermelon (Tokuda et al. 1995; Iida et al. 1995), cucumber (Arima et al. 1995), tomato (Monta et al. 1996), cabbage (Murakami et al. 1995), and mushroom (Reed et al. 1995). Kondo et al. (1994) developed several robotic harvesting hands for fruit vegetables including tomatoes, cherry tomatoes, and cucumbers.

Key Robotic Components

Manipulator

The basic mechanism of a manipulator is defined by its degrees of freedom, the type of joint, link length, and offset length. Any kind of manipulator may be used, if its work envelope includes the position of the work object and the work efficiency is not a major concern. This is because the principle task of a manipulator is to move and orient an end-effector to a position where it can interact with the work object. If a manipulator whose basic mechanism is not optimized for a particular production system is used, the work speed may be slow and the manipulator may only be able to place the end-effector at a singular point. This can potentially present some problems in a plant production system. The manipulator may have to risk a collision with the objects within the work envelope. Therefore, a mechanism optimized for the specific task is often required for a plant production robot. On the other hand, however, a manipulator which has a mechanism developed based on a specific operation is likely to have less flexibility in adapting to other operations. Nevertheless, a special purpose manipulator can still be used in performing various jobs by using different end-effectors. The factors normally considered in determining basic mechanism requirements for a manipulator of a plant production robot will be described in the following.

Work envelope:
As mentioned above, the role of a manipulator is to send an end-effector to a 3-D position within its work envelope. It is very common to have work objects presented by some sort of conveying system to a robot on a 2-D plane within a workcell. Work objects such as plants with fruit to be harvested or trays of plants to be worked on can be presented to a robot in the similar way. In such a case, many types of manipulator mechanism may be used; however, an appropriate spatial range for the positions of the work objects should be included within the work envelope. For field production, a large

work envelope is normally used to reduce the need of moving the manipulator. However, the most appropriate link length and degrees of freedom should be considered according to the application. In this case, the following normalized volume index Vn is used:

$$\mathrm{Vn} = \mathrm{V}/(4\pi \mathrm{L}^3/3) \tag{1}$$

where V is the volume of the work envelope and L is the total link length. It is, however, better to consider not only this index but the shape of the work envelope adaptable to the expected range of positions of work objects. This shape depends on the type and specific design of the manipulator.

Measure of manipulatability:
The configuration of a manipulator is evaluated by the measure of manipulatability which implies easiness to move the end of the manipulator. The measure of manipulatability, w, is defined, based on the Jacobian of the manipulator joint variables $J(\Theta)$, by Equation (2) (Yoshikawa 1983):

$$\mathrm{w} = (\det(\mathrm{J}(\Theta)\mathrm{J}^{\mathrm{T}}(\Theta)))^{1/2} \tag{2}$$

When a plant has many fruits to be harvested, this index is important for a high work efficiency of the harvesting robot. For example, when the elbow angle is 90 degrees in case of a 2 DOF manipulator consisting of elbow and wrist joints, the measure of manipulatability is maximum. It is understandable that a human's hand is easily moved when its elbow is bent at around 90 degrees. The basic mechanism should be determined so that the measure of manipulatability has a large value when the manipulator takes a configuration for operation.

Posture diversity:
If a manipulator has more than 7 DOF, it has redundant space. This means that the manipulator can have an access to the object through plural routes. It also can be said that the manipulator can have the possibility to avoid an obstacle before approaching the target object if necessary. The posture diversity is defined by the angle at the redundant space as shown in Figure 1 (Okamoto et al. 1992; Kondo et al. 1993).

There are several other evaluation indices for the mechanism of a manipulator such as: positioning accuracy of the manipulator end, ease of control of the manipulator and so on (Okamoto et al. 1992). Figure 2 shows a mechanism for a tomato harvesting manipulator (Kondo et al. 1993) as an example using the above evaluation indices. This is based on the conventional tomato plant training system like the configuration of a fence on a vertical plane in which tomato plants are grown until six or seven trusses of fruit are harvested.

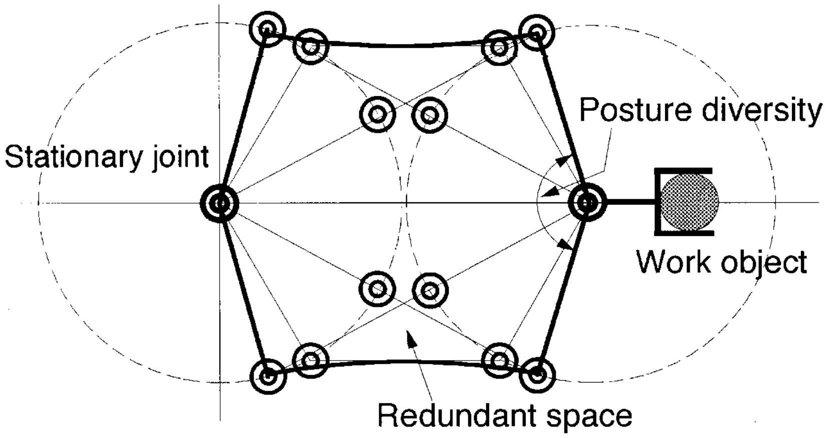

Figure 1. Posture diversity.

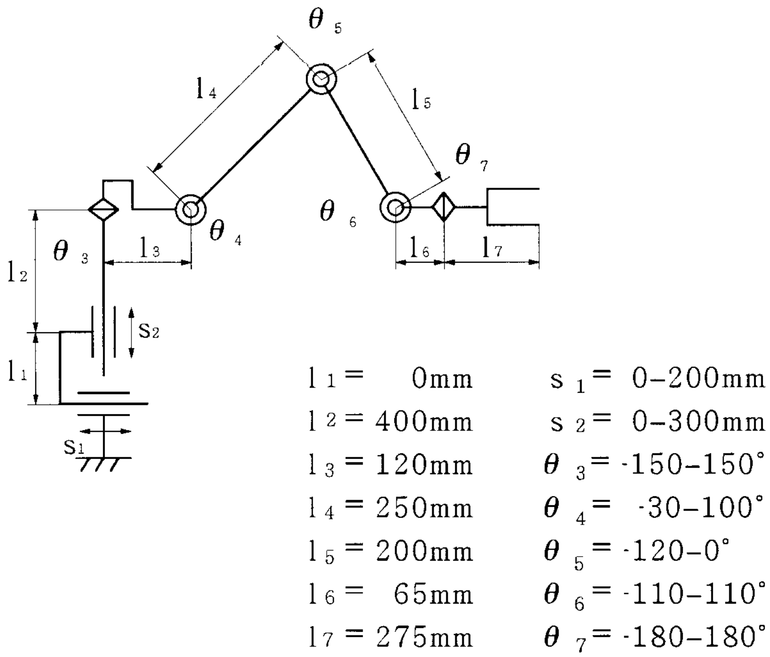

Figure 2. Basic mechanism of a tomato harvesting manipulator.

This manipulator shown has 7 degrees of freedom. If this manipulator is used for a harvesting operation it is easy for the manipulator end to approach any fruit in the plant with high manipulatability.

End-effector

A specific mechanism for an end-effector depends on a specific work object and an operation to be performed. Since the properties of the work object the robot directly handles and the type of operation are different from any others this should be unique. Most of objects for plant production systems have various sizes and uncertain shapes, at least to some degree, even if they are same varieties. They are usually much softer than the materials of the robot and are usually easily damaged. Before designing a specific end-effector, therefore, many kinds of physical properties of its intended work object should be measured such as: shape, size, mass, cutting resistance, frictional resistance, elasticity, viscosity and so on according to the operation to be performed. When those properties are not the only ones required to develop the end-effector, optical, sonic and electrical properties are also often required. In addition, chemical and biological properties sometimes may be necessary. The end-effector developed based on such specific properties is usually not for multi-purpose use but for specific use to achieve highly efficient work. It often has to have sensors so as not to injure the object and to compensate for errors of another sensor, since handling of the object by the end-effector influences product market value.

Figure 3 shows a cherry tomato harvesting end-effector (Kondo et al. 1995). This end-effector pulls a fruit into its tube opening pneumatically by suction. Three pairs of photo-sensors detect the fruit location in the end-effector. If the fruit comes to an appropriate position, its peduncle will be nipped at the joint by the action of the nipper closing. The fruit which has been detached from its peduncle will be transported to a container through the tube by suction. Small fruit like cherry tomatos or strawberries can be harvested by this kind of end-effector. However, the tube must be designed so that fruit is not injured when it is transported.

Visual sensor

A visual sensor is a very important external sensor of a robot just like the eyes for humans. The three important functions of visual sensors for a plant production robot are: discrimination, recognition, and distance measurement. The work objects may have specific optical properties (as the examples shown in Figure 4), uncertain shape, and various positioning possibilities. Figure 4 shows that there are differences in the color of plant material within the visible region which a human being can normally detect. Plant reflectance in the infrared region depends on the part of plant from which energy is reflected. It is interesting that reflectances of fruits are classified into two groups. One group has higher reflectance than that of leaves within the waveband of

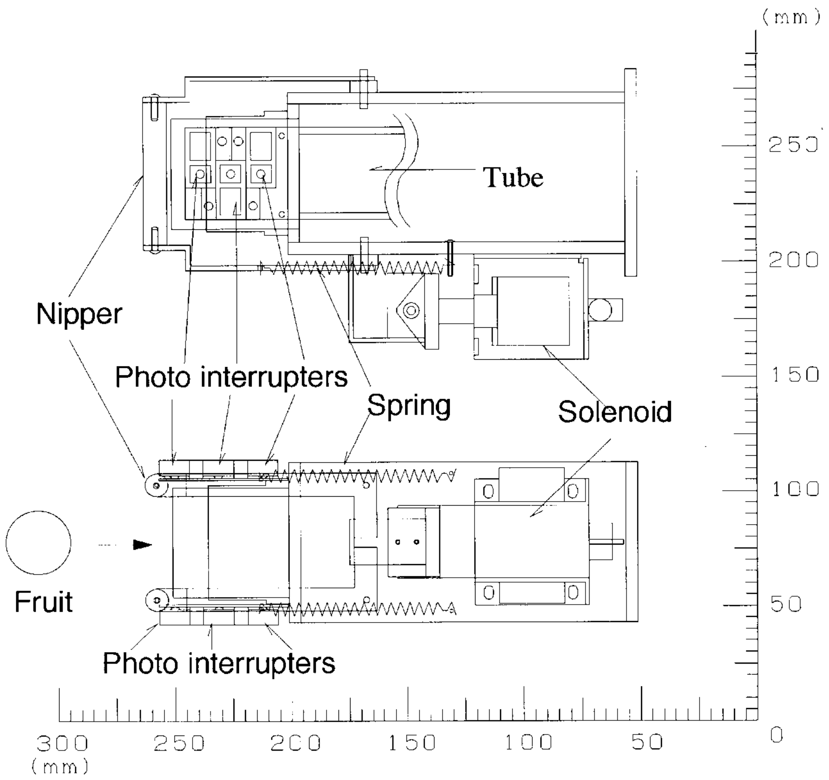

Figure 3. End-effector for cherry tomato harvesting.

700 nm to 1100 nm. The reflectance of the other group is lower than that of leaves. The difference seems to be caused by the difference of the state of water in the surface of fruit, since most of fruits are juicy in the latter group. Fruit and stem have water absorption bands at 970 nm and 1170 nm in their reflectances. Flowers and leaves have no absorption band because of their thinness. Most plants have these characteristics of reflectances as shown in Figure 4, so these characteristics should be used for effective discrimination of the work object by a visual sensor.

Discrimination:
When the color of a work object is different from that of the others, it is not so difficult to discriminate the work object in the image by using R, G, B signals from a color TV camera. For example, ripe tomato fruit and leaves can be discriminated by comparing red with green signals. When unripe tomato fruit is discriminated from green color leaves and stems, it is necessary to

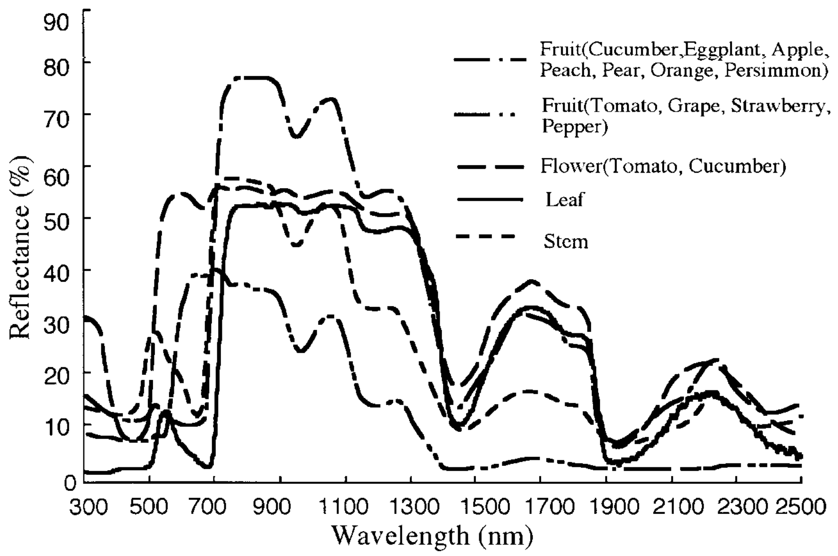

Figure 4. Spectral reflectance of plant materials.

acquire images through 670 nm and 970 nm interference filters (Kondo and Endo 1987). The 550 nm and 850 nm interference filters are effective for discrimination of green cucumber fruit (Kondo and Endo 1987; Kondo et al. 1994), where 670 nm is the chlorophyll absorption band, 970 nm is the water absorption band, 550 nm is the center of wavelength for the green color and 850 nm is the wavelength at which there is significant difference in reflectance between fruit and leaf. These wavelengths are so important that even green color fruit can be effectively discriminated from the others in the acquired image.

Recognition:
A thresholded image which mainly consists of work objects can be obtained after comparing the images acquired through the same specific optical filters as used for discrimination. It is necessary to recognize the size, direction, shape, number and so on of work objects in the image for handling the object. Before recognizing the blob, or outline of the object, some processing is sometimes conducted for the binary image such as smoothing, contraction, dilatation, thinning, border following, edge detection, noise reduction and so on. This is because the image often has not only the work object but also noise and unnecessary substances. When the characteristics of the object are recognized, it is important to extract some features from the image. The features for shape recognition are very many, such as area, perimeter, Feret's diameters, moment,

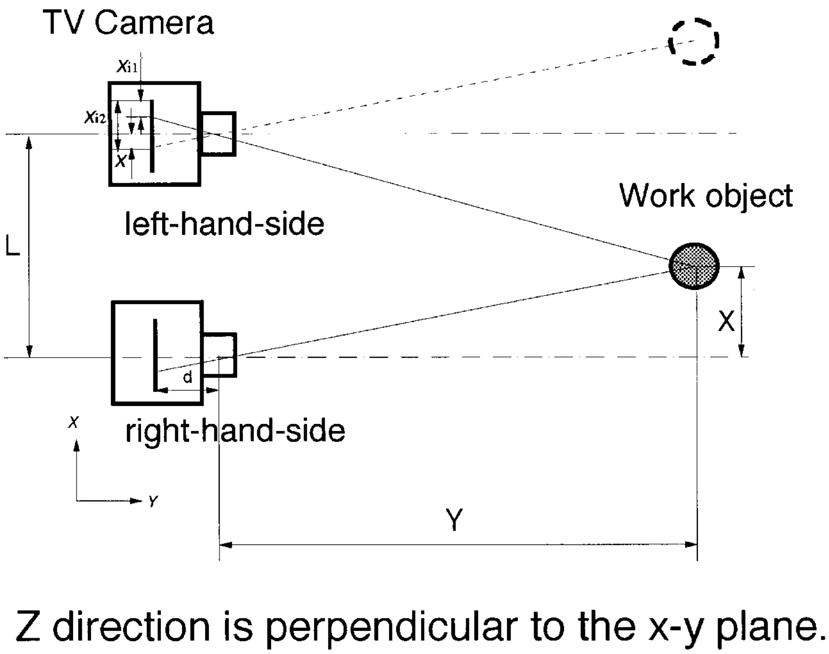

Figure 5. Binocular stereo vision.

fractal dimension, intersection, orientation and so on. Furthermore, textual features extracted from gray level image are sometimes necessary such as angular second moment, contrast, inverse difference moment, correlation and so on (Haralick et al. 1973).

Distance measurement:
Distance measurement is essential for robotic operation. Several methods based on the principle of triangulation have been reported previously. The most well-known method is binocular stereo-vision. If two images (of the same object) are acquired at different places, the distance from the visual sensor to objects can be measured. The distances Y and X in Figure 5 are calculated by Equation (3).

$$\mathrm{Y} = \mathrm{dL}/(\mathrm{x}_{i2} - \mathrm{x}_{i1}), \qquad \mathrm{X} = \mathrm{xY}/\mathrm{d} \tag{3}$$

A visual sensor can be attached to the manipulator end of a robot system, because the position of a visual sensor can be strategically changed to utilize the pixel number of visual sensor efficiently and to have possibility to detect the object hidden by an obstacle. When the visual sensor is attached

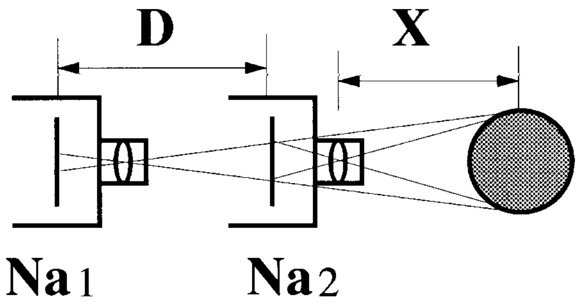

Figure 6. Differential object size method.

to the manipulator end, the sensor moves to the object with the manipulator approaching. The distance X in Figure 6 is calculated by Equation (4), because the number of pixels representing the object is increasing when the manipulator is moving toward the object.

$$X = D(Na1)^{1/2}/((Na2)^{1/2} - (Na1)^{1/2}) \tag{4}$$

where Nai is the number of pixels representing the object in the i-th image (i = 1, 2), and D is the visual sensor moving distance.

These methods are classified into a category of passive range finder method. On the other hand, there is an active range finder method measuring by projecting light and receiving it. If the light is scanned horizontally and vertically, a 3-D sensing capability can be achieved. In addition, if a red light beam and infrared light beam are used as the projected lights, not only distance information but color information can be obtained (Fujiura et al. 1992).

One more important thing is that the visual sensor for a plant production robot is often used in the field or in a greenhouse where illuminance and the color temperature of sunlight are changing from time to time. The influence of the various conditions of sunlight should be eliminated. Using a pair of optical filters based on the spectral reflectance of an object can solve these problems. This is specially important in a greenhouse where the visual sensor may be used under the condition of high temperature and high humidity. Needless to say, the most simple, light and inexpensive sensor is desired.

Travelling device

When the work object is a small and portable object, such as a harvested fruit, a seedling or its tray, the robot can be stationary (Ting et al. 1990). In such circumstances the work object is much more easily transported than the robot. The robot itself can also be stationary in the cases where the work object is positioned for the robot independantly, as with a conveyor or some other simple, non-robotic positioning device. However, the robot often has to move by itself in the field or from place to place within a greenhouse. This is required when the object is not portable, such as fruit, flower or grain attached to a plant which is itself immovable in the soil, or when the operation should be conducted in the field. In such a case, the robot needs its own travelling device.

Automatic controls of the most common types of traveling devices of wheel (Yamashita et al. 1992), rail (Itokawa 1990), crawler (Kondo 1993) and gantry system (Miyazawa 1987) have been reported. The wheel type has a simple structure and is easily used, so some autonomous vehicles for applications such as sprayer operation or simple transport have already been commercialized. The rail type traveling device is effective in the intensive production areas in structures such as greenhouses or terraced orchards. The initial cost for the rail is quite expensive and maintenance of the rail is necessary, but such a device is relatively easy to control. The crawler type is needed for the transportation of large robots to reduce pressure on ground. In some fields where a gantry system can be installed, it is relatively easy to introduce a robot and it is not necessary to worry about pressure on the ground, because its wheels and rails are on levees of the field. In a gantry system, high precision for positioning and stability of robotic motion can be obtained, however there are fields where the gantry system installation is difficult.

Horticultural Approach for Robotic Development

As described above, each component for a plant production robot must be developed based on the physical properties of its work object. The horticultural aspects of the production system must also be considered to realize the practical use of various kinds of robots. For example, plant training systems and cultivation methods have been developed so that productivity and quality can be improved and that the farmer can work easily. But the robot cannot often work efficiently in the present training system, since its eye, arm, hand and leg are inferior to those of the farmer. These factors can prevent the practical use of the robot. There are, therefore, trials underway to change the conventional plant training system into a new training system adaptable not only to farmer's operation but also to robotic operation. Cultural systems can be developed to facilitate cooperative work between human operators and robots.

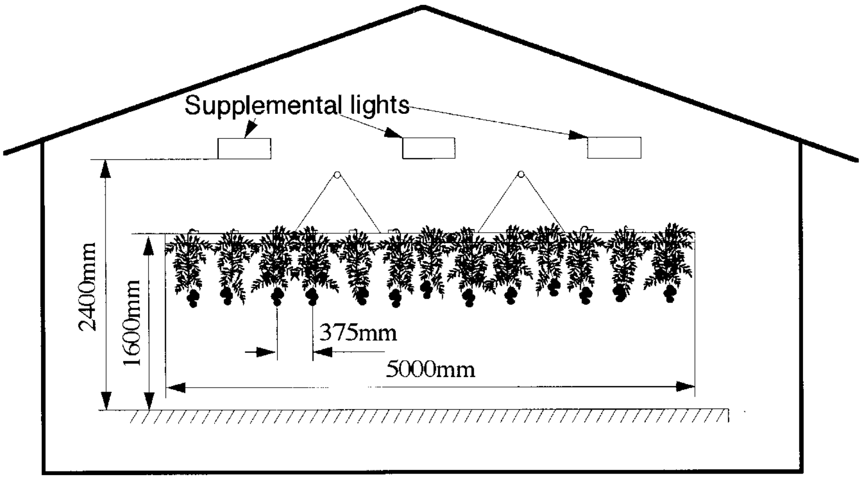

Figure 7. Upside down single truss tomato production system.

Figure 7 shows a new plant training system for tomato plants (Monta et al. 1996). This is called the upside down single truss tomato production system. The plant and fruit trusses hang down from the trough so that robot can find fruits and can have an access to fruits easily from underneath or the sides. This system was proposed to realize several potential advantages as follows: (1) tomato plants including seedling, truss, fruit, leaf and stem can be standardized, (2) uniform quality and quantity are expected, (3) production scheduling is easy and demand of labor is predictable, (4) a transportable bench or flume is easily used and greenhouse space is efficiently utilized, (5) mechanization is relatively easy, and (6) much less labor for plant training is required.

Configuration of some plants can be also changed during growing under controlled environment. When difference of temperature between day time and night time is appropriately controlled (Heins and Erwin 1990) or when irrigation or fertilization is changed, morphological features of the plants are changed. Appropriate environmental control for a plant production robot may be required for its practical application. From another viewpoint, such control can facilitate standardization of plants. It is expected that the robot can work much more easily, if the size, shape, position and growth habit of the objects have been standardized by environmental control. In addition, if a data base for a standardized plant can be accumulated as knowledge for the robot, the possibilities for intelligence based control algorithms for the robot increase.

It will also be important to choose a suitable variety for robotic operation. For example, an experimental result of robot harvesting says that a longer peduncle is better for robot harvesting of many fruits (Kondo et al. 1994). If the peduncle is too short, there is a risk to injure fruits or stems and the success rate of harvesting may decrease. A new variety of plant may be developed for robotic operation based on the genetic engineering approach in the near future.

There have been many trials to change training systems and morphological features for plant production robots for harvesting crops such as tomato, cherry tomato, cucumber, strawberry, etc. When a plant production robot is to be developed, consideration of effectively integrating horticultural technologies and robotic technologies is essential.

Conclusion

The plant production robots are different from the industrial robots mainly due to the need to integrate engineering technologies with agricultural/horticultural technologies. Both robotics and horticultural technologies are now progressing rapidly. It is, therefore, important that engineers and plant scientists work closely together in the development of robotics for plant production. Furthermore, economic consideration is also an important aspect of robotic development. There have been many research and development projects on horticultural robotics with impressive results; however, the utilization of robotics in plant production is still limited compared to its use in the manufacturing industry. There are undoubtedly some interesting challenges and exciting opportunities existing in the development of robotics for plant production.

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