The complex agricultural environment combined with intensive production requires development of robust systems with short development time at low cost. The unstructured nature of the external environment increases chances of failure. Moreover, the machines are usually operated by low-tech personnel. Therefore, inherent safety and reliability is an important feature. Food safety is also an issue requiring the automated systems to be sanitized and reliable against leakage of contaminations. This chapter reviews agricultural automation systems including field machinery, irrigation systems, greenhouse automation, animal automation systems, and automation of fruit production systems. Each section describes the different automation systems with many application examples and recent advances in the field.

63.1 Field Machinery

63.1.1 Automatic Guidance of Agricultural Vehicles

63.2 Irrigation Systems

63.2.1 Types of Irrigation Systems

63.2.2 Automation in Irrigation Systems

63.3 Greenhouse Automation

63.3.1 Climate Control

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63.3.3 Automatic Sprayers

63.3.4 Fruit Harvesting Robots

63.4 Animal Automation Systems

63.4.1 Dairy

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63.4.3 Poultry

63.4.4 Sheep and Swine

63.5 Fruit Production Operations

63.5.1 Orchard Automation Systems

63.5.2 Automation of Fruit Grading and Sorting

63.6 Summary

References
tural automation systems may be much lower. Since the product being dealt with is of relative low cost, the cost of the automated system must be low in order for it to be economically justified. The seasonal nature of agriculture makes it difficult to achieve the high utilization found in manufacturing industries.

63.1 Field Machinery

The use of machinery in agriculture has a long history, but the most significant developments occurred during the 20th century with the introduction of tractors. As early as 1903, the first farm tractor powered by an internal combustion engine was built by Hart Parr Company. Using its assembly line techniques, Henry Ford & Son Corporation started mass production of Fordson tractors in 1917. The commercial success of tractors sparked other innovations as well. In 1924, the International Harvester Company introduced a power takeoff device that allowed power from a tractor engine to be transmitted to the attached equipment such as a mechanical reaper. Deere & Company followed in 1927 with a power lift device that raised and lowered hitched implements at the end of each row. Rubber wheels were first designed and used for tractors in 1932 to improve traction and fuel economy. Pulled and powered by tractors, an increasingly wide range of farm implements were developed in the 20th century to mechanize crop production in every step, from tillage, planting, to harvesting. Harvesting equipment trailed only tractors in importance. Early harvesters for small-grain crops were pulled by tractors and powered by tractors’ power takeoff (PTO). The development of a self-propelled combine in 1938 by Massey Harris marked a significant progress in increasing productivity. The self-propelled combine incorporated several functions such as vehicle propulsion, grain gathering, and grain threshing into an all-in-one unit for better operation efficiency. The mechanization of harvesting other crops included the developments of mechanical hay balers in the 1930s and mechanical spindle cotton pickers in 1943. Tractors, combines, and other farm machinery were continuously refined during the second half of the 20th century to be more efficient, productive, and user-friendly. The success of agricultural mechanization has built a strong foundation for automation. Automation increases the productivity of agricultural machinery by increasing efficiency, reliability, and precision, and reducing the need of human intervention [63.1]. This is achieved by adding sensors and controls. The blending of sensors with mechanical actuation can be found in many agricultural operations such as automating growing conditions, vision-guided tractors, product grading systems, planters and harvesters, irrigation, and fertilizer applicators. The history of automation for agricultural machinery is almost as old as agricultural mechanization. Two ingenious examples in the early 20th century were the self-leveling system for hillside combines by Holt Co. in 1891 and the implement draft control system by Ferguson in 1925 [63.2]. Early automation systems mainly used mechanical and hydromechanical control devices. Since the 1960s, electronics development for monitoring and control has dominated machine designs, and has led to increased machinery automation and intelligence. Mechatronics technology, a blend of mechanics, electronics, and computing, is often applied to the design of modern automation systems. Automation in contemporary agricultural machines is more complicated than a single control action; for example, the modern combine harvester has automatic control of header height, travel speed, reel speed, rotor speed, concave opening, and sieve opening to optimize the entire harvest process. Farm machinery includes tractors and transport vehicles, tillage and seeding machines, fertilizer applicators and plant protection application equipment, harvesters, and equipment for post-harvest preservation and treatment of produce. Mechanization and automation examples can be found in many of these machines [63.3]. However, the wide variety of agricultural systems and their diversity throughout the world makes it difficult to generalize about the application of automation and control [63.1]. Therefore, only one type of automation – automated navigation of agricultural vehicles – will be presented here. Automated vehicle navigation systems include the operator-assisted steering system, automatic steering system, and autonomous system. These systems can relieve the vehicle operator of the repetitive and monotonous steering operation. Automatic guidance has been the most active research area in the automation history of agricultural machinery. With the introduction of the global positioning system (GPS) to agriculture in the late 1980s, automatic guidance technology has been successfully commercialized. Today, autoguidance is the fastest growing segment in the agricultural machinery industry. The following sections discuss the principles of autoguidance systems, the
available technologies, and examples of specific autoguidance systems.

63.1.1 Automatic Guidance of Agricultural Vehicles

For many agricultural operations, an operator is required to perform two basic functions simultaneously: steering the vehicle and operating the equipment. The need to relieve the operator of continuously making steering adjustments has been the main reason for the development of automatic guidance systems. Excellent references to automatic vehicle guidance research in Canada, Japan, Europe, and the USA can be found in Wilson [63.4], Torii [63.5], Keicher and Seufert [63.6], and Reid et al. [63.7]. Figure 63.1 shows a typical autoguidance system which includes a position sensor, a steering angle sensor, and a steering actuator as the hardware components, and a path planner, a navigation controller, and a steering controller as the software components. The path planner gives the desired (or planned) vehicle position. This desired position is compared with the measured position given by the position sensor. The navigation controller calculates the desired steering control angle based on the difference in the desired and measured positions. Finally, the steering controller uses the difference in the desired and measured steering angles to calculate an implementing steering control signal and sends it to drive the steering actuator. Modern agricultural vehicles often employ electrohydraulic (E/H) steering systems. Developments in each of the system components are described in details below.

Position Sensing

The position sensing system measures vehicle position relative to a reference frame and provides inputs to the navigation controller. Most agricultural guidance applications require position measurement in two-dimensional (2-D) space. In addition, vehicle speed, heading, and rotational movements (roll, pitch, yaw) are often needed by the navigation controller.

Guidance accuracy is the primary factor in selecting a position sensor. Auernhammer and Muhr [63.8] suggested three levels of accuracy required for different farming operations: 1 m for rough operations (soil sampling, weed scouting), 10 cm for fine operations (pesticide application, soil cultivation), and 1 cm for precise operations (planting, plowing). Different position sensors are selected in a guidance system to meet the accuracy requirements for different farming operations. In general, there are three categories of positioning techniques: absolute positioning, relative positioning, and sensor fusion.

Absolute Positioning. The most common system of absolute positioning is the global navigation satellite system (GNSS). Currently, the NAVSTAR global positioning system (GPS) in the USA is the only fully operational GNSS. A GPS receiver calculates its position by measuring the distance between itself and three or more GPS satellites. The positioning accuracy of an autonomous, mobile GPS receiver is 5–15 m. This accuracy is generally not suitable for vehicle guidance. To improve the accuracy, a differential correction technique is applied. A differential GPS (DGPS) receiver can provide position accuracy within 2–5 m and within 1 m precision in a short time period. The DGPS receiver’s accuracy can meet the requirement of positioning accuracy for most guidance applications. Further improvement in GPS accuracy requires carrier-phase enhancement (or a real-time kinematic process), typically using a local base station. The real-time kinematic GPS (RTK GPS) receiver can achieve centimeter accuracy and should meet the positioning accuracy requirements for almost all agricultural field operations. The GPS positioning technique has been successfully implemented for vehicle guidance since its inception [63.9–12]. Other absolute positioning sensors, such as laser [63.13] and geomagnetic direction sensors [63.14], have been developed and applied to vehicle guidance with varying degrees of success. However, currently the GPS receiver remains the only commercially viable choice for absolute positioning systems.

Relative Positioning. The most promising system of relative positioning is computer vision using cam-
Vision-based sensing is mainly used for automatic guidance in row crops. Its operation resembles a human operator’s steering of the vehicle – the camera is equivalent to the eye and the vision processor is equivalent to the brain. The main technical challenge to vision guidance is using image processing to find a guidance directrix, i.e., the position and orientation of the crop rows relative to the vehicle. Numerous image recognition algorithms, such as Bayes classification, edge detection, K-means clustering, and the Hough transform, have been developed since the 1980s [63.15–19]. Vision-based system can achieve excellent positioning accuracy under good crop and ambient light conditions; for example, Billingsley and Schoenfisch [63.20] reported 2 cm accuracy for their vision guidance systems. Han et al. [63.19] reported 1.0 cm average root-mean-square (RMS) offset error for soybean images and 2.4 cm for corn images. However, the vision-based system may not be reliable under changing lighting conditions, which are not uncommon in an agricultural environment. Other relative positioning sensors include dead reckoning, odometry, and inertial measurement units (IMU). These sensors are seldom used alone in a vehicle navigation system. Instead, they are integrated with absolute positioning sensors (e.g., GPS) in a sensor fusion approach.

Sensor Fusion. Sensor fusion is the process of combining data from multiple sensors so that the resulting information is better than when these sensors are used individually. No single positioning sensor will work for agricultural vehicle guidance under all conditions; for example, a GPS signal may be blocked by heavy tree shading. Vision sensors may not work under heavy dust conditions. Sensor fusion not only provides a way to automatically switch to a working sensor when one of the sensors quits working, but also blends the outputs from the multiple working sensors to obtain the best results. A good example of sensor fusion is integration of GPS with inertial sensors [63.21]. In this approach, GPS provides the low-frequency absolute position information, and inertial sensors provide the high-frequency relative position information. Inertial sensors can smooth out the short-term GPS errors, and the GPS can correct the bias and scale factor errors of the inertial sensors. If the GPS signals become temporarily unavailable, the inertial sensors can continue to provide position information. Sensor fusion allows the integration of several low-cost sensors to achieve good positioning accuracy [63.22]. Many algorithms are available for sensor fusion [63.23], with the Kalman filtering technique being the most common approach [63.24]. Adaptive sensor fusion algorithms have also been developed to deal with a priori unknown sensory distributions and asynchronous update of the sensors [63.25]. Terrain compensation is another example of applying sensor fusion to improve guidance accuracy on sloping terrain. A terrain compensation module measures vehicle roll, pitch, and yaw angles, and combines these measurements with the position measurement to compensate for the GPS antenna movement due to side slopes and rough terrain. Many manufactures of autosteering systems now offer terrain compensation features. Additional information on sensor fusion can also be found on Chap. 20.

Path Planning
Path planning is the generation of 2-D sequenced positions or trajectories for the automated vehicle. The sequenced positions account for the vehicle kinematics such as the minimum turn radius and other constraints. Most agricultural operations, such as tillage, planting, spraying, and harvesting, require the vehicle to travel the entire field with parallel paths at a fixed spacing equaling the implement width. Planning such paths is called coverage path planning. Coverage path planning involves two steps. Step one is to decompose a field into subregions. An optimal travel direction is found for each subregion. Step two is to find the optimal coverage pattern within each subregion. Many different algorithms have been developed for coverage path planning [63.26].

Trapezoidal decomposition is a popular technique for subdividing the field. The trapezoids are then merged into larger blocks and the selection is made using certain criteria which take into consideration the area and the route length of the block and the efficiency of driving [63.27]; Jin and Tang [63.28] used a geometric model to represent the full coverage path planning problem. The algorithm was capable of finding a globally optimal decomposition for a given field and the direction of the boustrophedon paths for each subregion. The search mechanism of the algorithm is guided by a customized cost function that unifies different cost criteria, and a divide-and-conquer strategy is adopted.

A graphical approach is often used to find the optimized coverage pattern within a subregion [63.29–31]. The processes include partitioning the area, building a partition graph, and searching the partition graph. Heuristic functions are used in the searching process to prune the search tree early so the optimized solution can be found within a reasonable time. In the case of mul-
tiple vehicles working in the same region, Gray [63.32] developed a path planning method.

**Navigation and Steering Controllers**
The navigation controller takes the desired and measured positions as inputs to compute the desired control variables, typically the lateral and heading corrections. The desired control variables and the measured variables (typically the steering angle) are fed into the steering controller to compute the steering corrections. A typical navigation control algorithm calculates the lateral and heading errors based on a reference point on the vehicle and a target (look-ahead) point on the desired vehicle trajectory. The target point may be dynamically adjusted based on speed to achieve satisfactory path tracking performance [63.33, 34].

Agricultural vehicles frequently operate in challenging conditions such as varying travel speed, operating load, and ground surface conditions. The steering controller design must be robust enough to adapt to these conditions. Several steering controllers, including proportional–integral–differential (PID) controller, feedforward PID (FPID) controller, and fuzzy-logic (FL) controllers, have been developed and implemented in the guidance system [63.35–37]. Additional information on mobility and navigation can be found on Chap. 16.

**Commercialization of Autoguidance Systems**
Commercial development of autoguidance systems by US manufacturers started in the 1990s soon after the availability of GPS to agricultural applications. Early GPS-based guidance systems used visual aids, commonly referred to as lightbars, to show a driver how to steer the vehicle along parallel passes or swaths across a field. The need to improve driving accuracy and repeatability led to the development of the next level of automation – autosteering. The autosteering system steers the vehicle within a path and the driver only needs to turn at the ends. Several preset driving patterns can be used by an autosteering system during field operations. The most popular patterns for ground applications are straight rows and curved rows. The straight-row option allows the operator to follow parallel straight paths separated by a predetermined swath width. An initial path (A–B line) is first defined by the operator and the remaining paths are generated by the guidance system. For the curved-row option, the operator drives the first curved path. The autoguidance system steers the vehicle along the consecutive paths. Other driving patterns such as circles (for center-pivot irrigation field) and spirals (for field headlands) are also available in some autoguidance systems. Autoguidance systems are now commercially available. Figure 63.2 shows an example of the GreenStar AutoTrac assisted steering system on a John Deere 8000 series tractor. Most autoguidance systems have reported a path-to-path accuracy better than 5 cm with DGPS or RTK under good field conditions.

**63.1.2 Autonomous Agricultural Vehicles and Robotic Field Operations**
An autonomous vehicle must be able to work without an operator. In addition to steering, it must perform other tasks that a human operator typically does: detecting and avoiding unknown objects, operating at a safe speed, and performing implement tasks while driving. Developing human intelligence for the autonomous vehicle is a challenging job.

Autonomous vehicles working in an unstructured agricultural environment must use sophisticated sensing and control systems to be able to react to any unplanned events. A typical unplanned event is the presence of a human or animal in front of the vehicle. Development of vehicle safeguarding systems is the key to the deployment of the autonomous vehicles. A number of technologies have been investigated for providing vehicle safeguarding. Guo et al. [63.38] used two ultrasonic sensors to detect a human being. The reliable detection range was up to 4.6 m for moving objects and 7.5 m for stationary objects under field conditions. Wei et al. [63.39] used a binocular stereo camera to detect a person standing in front of a vehicle. The system was...
able to find the person’s relative motion status (speed and heading) relative to the vehicle at a distance range from 3.4 to 13.4 m. Kise et al. [63.40] tried a laser rangefinder to estimate the relative motion of a tractor obstacle. In general, ultrasonic sensors are low cost but their detection range is short. Stereo cameras are unreliable under changing lighting conditions. Currently, the most reliable technology is the laser rangefinder, but its use is limited to research vehicle platforms due to the high costs. Multiple levels of system redundancy must be designed into the vehicle, which often requires multiple safeguarding sensors. Development of robotic field operations is an integral part of autonomous vehicles. In order to use an autonomous vehicle, tasks must be automated as well. Over the years, agricultural equipment has evolved to accommodate the automated control of tasks [63.1]. Microprocessor-based electronics control is replacing mechanical control, and electrohydraulically powered actuators are preferred over mechanically powered ones. The adoption of CAN bus standards (SAE J1939, DIN 9684, ISO 11783) in the agricultural equipment industry has allowed networking of multiple control systems.

Task automation examples can be found in many modern agricultural machines. Examples include map-based automatic spraying of fertilizer and chemicals on sprayers, and headland management systems (HMS) for automatic sequencing of tractor functions normally associated with headland turns. Matsuo et al. [63.41] described a tilling robot that was able to do tillage, seedling, and soil paddling operations. Reid [63.42] discussed a number of challenges related to the development of intelligent agricultural machinery and equipment. At present, autonomous agricultural vehicles and robotic field operations are still not reliable and durable enough to meet the requirements of the agricultural industry and its customers. Nevertheless, a number of autonomous vehicle systems have been developed as proof-of-concept machines which may lead to commercialization in the future. Some exemplary systems are briefly introduced below.

**Robotic Harvester**

A robotic harvester, called Demeter (Fig. 63.3), has been developed by the Carnegie Mellon University Robotics Institute for automated harvesting of windrowed crops. The robot platform was a New Holland 2550 self-propelled windrower equipped with DGPS, inertial navigation system (INS), and two color cameras. The camera system detected the cut/uncut edge of the crop, which gave a relative directrix for the harvester to follow. The camera system was also used to detect potential obstacles for vehicle safeguarding. GPS data was fused with vision data for guidance. In addition to steering, speed and header height of the harvester were also automatically controlled. In 1997, the Demeter autonomously harvested 100 acres of alfalfa in a continuous run (excluding stops for refueling). During 1998, the Demeter harvested in excess of 120 acres of crop, cutting in both sudan and alfalfa fields [63.43,44].

**Autonomous Tractor**

An autonomous tractor has been jointly developed by John Deere and Autonomous Solutions Inc. for automated spraying, mowing, and tillage in orchards (Fig. 63.4). The robot platform was a John Deere 5000 series tractor with significant modifications. The system components included the vehicle, a mobile control unit, and a base station; all were communicated
by a wireless CAN system. A DGPS and INS were used as positioning sensors. Vehicle controls included steering, brake, clutch, three-point hitch, PTO, and throttle. A long-range obstacle detection system was proposed for vehicle safeguarding. One of the key developments in the project was the path and mission planning, which included dynamic replanning for dynamic service events. The system design followed an industry joint architecture for unmanned ground systems (JAUGS) architecture. A proof-of-concept system was developed and successfully demonstrated, but the production decision was not made, primarily due to safety concerns.

**Small Robotic Platforms**

In agriculture, small robots can be used for many field tasks such as collection of soil or plant samples and detection of weed, insect or plant stress. When equipped with a larger energy source and appropriate actuators, they can also be used for localized treatments such as spot-spraying of chemicals or mechanical in-row weeding. A number of small robots have been developed, mainly at universities and research institutes [63.45]. Astrand and Baerveldt [63.46] developed an autonomous robot for mechanical weed control in outdoor environments. The robot employs a grey-level vision system to guide itself along the crop rows and a second, color-based vision system to identify the weed and to control a weeding tool that removes the weed within the row of crops. A plant nursing robot, HortiBot, was developed in Denmark as a tool carrier for precision weeding [63.47–49]. The HortiBot is a radio-controlled slope mower (Spider ILD01, Dvorák Machine Division, Czech Republic) equipped with a robotic accessory kit. A commercial stereo vision system was implemented for automatic guidance within plant rows.

**63.1.3 Future Directions and Prospects**

Farm productivity has increased significantly during the last century. Today, less than 3% of the US population works in agriculture, yet they produce more than adequate food for the entire nation. Agricultural mechanization has played a significant role in achieving this miracle. As next steps to mechanization, automation and robotization of farm operations can result in additional productivity improvement.

Autoguidance will continue to be the main focus of future development. The agricultural industry is now developing new systems for automation beyond autosteering of vehicles. Implement guidance and headland management are two examples. An implement guidance system automatically steers both tractor and implement and keeps the implement on the desired path. This helps overcome implement drift on hillsides or contour field conditions. The headland management system automates implement controls (e.g., to raise or lower the implement) and makes automatic turns at headland and interior field boundaries. Other guidance technologies that are close to commercialization include: sensor fusion that employs a multitude of complementary positioning sensors to improve system reliability, path or mission planning that produces the most efficient coverage paths for a single or multiple vehicles, and leader–follower systems for multiple-vehicle navigation and control, as in the case of combine harvester operation. Precision farming has become an area of enormous growth and excitement since the 1980s. The key concept in precision farming is to manage crop production at the subfield level. The labor-intensive nature of precision farming practices brings a great need for automated machines and equipment. Yield mapping and variable-rate application systems are now commercially available. In the future, autonomous field scout vehicles are needed for soil sampling, crop scouting, and real-time data collection. Small robots are desired for individual plant care such as precision weed control and selective crop harvesting. Because precision farming is considered as the future of agriculture, automation and robotics technologies will certainly become a big part of production agriculture in the 21st century.

**63.2 Irrigation Systems**

Irrigation is the supplemental application of water to the soil for assisting in growing crops. It is used mainly to replace missing rainfall for field crops, and to supply water to crops growing in protected environments such as greenhouses. The main objective is to supply the required amount of water to the plants at the right time. The types of irrigation techniques differ in how the water is distributed within the field. In surface irrigation systems water moves over the land by gravity and infiltrates into the soil. Surface irrigation systems include
furrow, border-strip, and basin irrigation. Localized irrigation systems distribute water in piped networks by pressure, and the water is applied locally in the field and to the plant. Localized systems include spray, sprinkler, drip, and bubble systems. Automation provides efficient on-farm use of water and labor for all methods by enabling flexible frequency, rate, and duration of water supply with control of the irrigator at the right application point [63.50].

### 63.2.1 Types of Irrigation Systems

Flood control automation includes optimal gate operation of irrigation reservoirs [63.51]; surge flooding, which enables release of water at prearranged intervals; telemetering of paddy ponding depth and canal water level [63.52], which can be used to capture runoff and pump it back into the field for reuse; and precision con-
control of inflow rate using ground-based remote-sensing feedback control systems [63.53]. Position of the advance of water along the furrow can be determined by contact-type sensors manually positioned in the furrow and recently by imaging systems [63.53, 54].

In sprinkler irrigation, water is piped to several locations in the field and distributed by high-pressure sprinklers or guns (Fig. 63.5). Spatially variable irrigation systems have typically used self-propelled irrigation systems – sprinklers mounted on moving platforms or center pivots [63.56, 57]. Center-pivot irrigation is a sprinkler irrigation system that is composed of several pipe segments joined together that are mounted on wheeled towers with sprinklers positioned along its length (Fig. 63.6). The system moves in a circular pattern.

Drip irrigation systems (Fig. 63.7) were invented in Israel in 1965. Water is applied slowly and directly to the soil, and only where needed. A drip irrigation system consists of valves, back-flow preventers, pressure regulators, filters, emitters, and of course the pipes (the mainline that leads water from the source to the valve, and the subpipe that goes from the valves to the connection point of the drip tubing and the drip tubes). Low-head bubbler irrigation systems are micro-irrigation systems based on gravity flow that operate at low pressure and require no filtration or pumping [63.58]. Their main advantages are simplicity, lower energy requirements, and few mechanical breakdowns [63.58]. However, their application is limited due to the complicated design and installation problems.

63.2.2 Automation in Irrigation Systems

Automation systems include irrigation time clocks – mechanical and electromechanical timers to allow accurate control of water responding to environmental changes and plant demands [63.59], with recent advances in using sensors to measure soil properties such as moisture and salinity using resistance- and capacitance-based sensors, and time-domain reflectometry [63.60, 61]. Sensors for measuring plant stress [63.62] by scanned and spotted canopy temperature measurements have been used in scheduling decisions for center-pivot and subsurface drip irrigation systems [63.63]. Sensors include infrared thermometers, thermal scanner sensors, and multispectral imaging [63.64].

High-resolution data of soil and water dynamics coupled with measurement of crop response to salinity and water stress are important for irrigation management optimization [63.65]. These data are commonly

![Wireless irrigation system conceptual layout](after [63.55])
provided by weight-based soil lysimeters, with recent development of a volumetric lysimeter system [63.65].

Developments in automated irrigation systems include scheduling programs that use weather data to recommend and control time and amount of irrigation, crop growth stage and water/nutrients needs detected in real time, and commercial yield monitors and remote sensors to map crop production precisely. An example includes a real-time irrigation scheduling program for supplementary irrigation that includes a reference crop evapotranspiration model, an actual evapotranspiration model, a soil water balance model, and an irrigation forecast model, all combined using a mixed linear program [63.67, 68].

Low-cost microprocessor and infrared sensor systems for automating water infiltration measurements [63.69] are important in controlling crop yields and delivering water and agricultural chemicals to soil profile. Control of nutrients with sensors enables optimization of irrigation and fertilization management systems, useful for reducing environmental impact caused by runoff of nutrients into surfaces and groundwater by using ion-sensitive field-effect sensors [63.70].

A wireless in-field sensor-based irrigation management system was developed to provide variable-rate irrigation. Variable-rate irrigation was controlled by a computer that sends control signals to irrigation controllers via real-time wireless communications based on field information and GPS positions of sprinklers [63.55, 66, 71, 72]. A self-propelled linear sprinkler system equipped with a DGPS and a program logic controller was remotely controlled by a base computer [63.72, 73], using a closed-loop irrigation system to determine the amount of irrigation based on distributed soil water measurements (Figs. 63.8 and 63.9). The system was operated by a program logic controller that controlled solenoids to turn sprinkler nozzles on and off. Variable-rate application was implemented by regulating pressure into a group of nozzles.

### 63.3 Greenhouse Automation

The greenhouse environment is a relatively easy environment for introduction of automated machinery due to its structured nature. Hence, the automated system must deal only with the variability of the agricultural product. Therefore, the development of systems is easier and simpler. Automation systems for greenhouses deal with climate control, seedling production, spraying, and harvesting as detailed in the following sections.

#### 63.3.1 Climate Control

Greenhouses have been developed during the 20th century to keep solar radiation energy, to protect products from various hazardous natural climates and insects, and to produce suitable environments for plants by use of 100 μm plastic film or 2–3 mm glass plates. Advances in sensors and microcomputers have led to
modern greenhouse operations that include control of climate, irrigation, and nutrient supply to plants to produce the best conditions for crop growth in an economical way. Environmental control enables year-round culture and shorter cultivation periods. This section outlines greenhouse environment control and automation.

Parameters and Sensors for Environmental Control

Light. Generally, there are two types of light: sunlight and artificial light from lamps. Visible light (400–700 nm, photosynthetically active radiation) is important for plant growth. Photosynthetic photon flux density (PPFD, measured in μmol m$^{-2}$s$^{-1}$) from photon sensors is appropriate when light intensity is measured for plant growth, while intensity of illumination (lux) is measured based on human sensitivity [63.77]. Although intensity and color temperature of sunlight vary from time to time and from place to place, artificial lighting devices can change them more drastically. There are several popular lighting devices: incandescent lamp, fluorescent lamp, high-intensity discharge lamp (HID lamp: Hg lamp, Na lamp, metal halide lamp), light-emitting diodes (LED), electroluminescence (EL), hybrid electrode fluorescent lamp (HEFL), and others. It is necessary to use them based on size, shape, efficiency, light intensity, life, color rendering, and color temperature of the lamp [63.78].

Temperature and Humidity. Heating and cooling in greenhouses are important for plant growth. Due to the amount of energy consumed for these operations, their control is critical. Electric heaters are used when it is necessary to specifically heat local sections such as in seedling production. Radiation in greenhouses that use sunlight can cause high air temperatures. Hence, cooling is necessary. To reduce cooling costs, curtain, infrared absorption glass (80% transmittance in visible region and 20% in infrared region), watering on glass roof, whitening the cover material, fan and pad system, fan and mist system, fog and fan system, and other methods are employed [63.79]. The thermocouple sensor is a popular measure of air temperature, while a thermo-camera and other radiation thermometers can measure radiant energy from plant parts or material bodies. Several types of humidity sensors are available: elemental devices whose electrical resistance, capacitance, or impedance is changed with humidity change. The sensors can measure 10–90% relative humidity. Humidity in greenhouses is influenced by air temperature control, transpiration from plants, water evaporation from soils, and other effects; for example, the fog and fan system can decrease temperature by 2°C and increase humidity by 20% as compared with external air [63.80]. To reduce humidity, an electric cooling machine is sometimes used, while air ventilation is the simplest method. Thus, humidity control also requires compensation of temperature change. When greenhouse environments are controlled, both heat balance and moisture budget must be considered. PID and adaptive control methods have been developed for temperature and humidity control [63.81–83].

CO$_2$ Concentration. Plants absorb CO$_2$ and transform it into sugars and then into new plant tissue [63.84]. Every gram of CO$_2$ fixed by the plant yields around 10 g of new plant material. This so-called photosynthesis (or CO$_2$ assimilation) requires good light and suitable growing conditions. Plants consume more CO$_2$ under more light and also at higher CO$_2$ level. By CO$_2$ enrichment the CO$_2$ uptake can be increased. The effect of CO$_2$ on yield is proportional to the amount of time of CO$_2$ enrichment.

CO$_2$ uptake depends on the crop, the leaf area, and environmental conditions such as soil moisture and atmospheric humidity. It is expressed in gram CO$_2$ gas per m$^2$ ground area per hour (g m$^{-2}$ h$^{-1}$). CO$_2$ uptake varies from 0 during very poor conditions to about 5 g m$^{-2}$ h$^{-1}$ under excellent light conditions, and up to 7 g m$^{-2}$ h$^{-1}$ under excellent light conditions combined with high CO$_2$ levels. At night no CO$_2$ is taken up; in contrast, plants produce CO$_2$ due to respiration. Hence the CO$_2$ level in a closed greenhouse naturally increases overnight to above-ambient levels.

Ventilation influences the CO$_2$ level, which has three situations:

1. CO$_2$ depletion: the CO$_2$ level is below ambient. Any leakage or ventilation will bring CO$_2$ into the greenhouse. Ample ventilation can prevent CO$_2$ depletion.
2. Elevated CO$_2$ levels due to CO$_2$ enrichment. CO$_2$ gas will rapidly be lost during venting, depending on the vent opening, wind speed, and CO$_2$ level.
3. When the CO$_2$ level in the greenhouse is equal to the level outside. The influx of fresh air plus the CO$_2$ supply exactly compensates the CO$_2$ absorption. In this situation there is no CO$_2$ loss. The CO$_2$ demand equals the CO$_2$ absorption by the plants plus the CO$_2$ lost by leakage or ventilation.
However, the benefits of CO₂ enrichment should outweigh the costs. This depends on the yield increase due to CO₂, as well as on the price of the produce. Moderate CO₂ enrichment is sometimes more economic than excessive enrichment. CO₂ enrichment should not go beyond 1000 ppm, as it is not beneficial for the plants and is unnecessarily expensive. Sensitive plants (e.g., young or stressed plants, sensitive species) should not be exposed to more than 700 ppm CO₂. Too high CO₂ levels cause partial closing of the pores in the leaves, which leads to low growth. Also, at higher CO₂ concentration, there is higher risk of accumulation of noxious gases that can be present in the CO₂ gas.

**Air Flow.** It is important to keep uniform temperature, humidity, and CO₂ in the greenhouse for proper plant culture and uniform growth. Air flow in greenhouses is achieved in different ways depending on the greenhouse structure. Natural ventilation is usually used due to its low costs. However, control of airflow with natural ventilation is limited. Therefore, it is necessary to analyze natural ventilation properly and increase ventilation efficiency. Natural ventilation is driven by pressure differences created at the vent openings both by wind and/or temperature differences. Prediction of air exchange rates and optimization of greenhouse design requires complicated models due to the coupling and nonlinearities in the energy balance models. Additional controls of air flow include on/off control of fan ventilation systems, side openings, and water sprayers [63.85] with recent developments in rate control achieved by PID or fuzzy-logic control.

**Control Methods**

Greenhouse climate control requires consideration of many nonlinear interrelated variables. Control models should take into account weather prediction models, crop growth models, and the greenhouse model. The following methods have been used for control: classical methods (proportional integral derivative control, cascade control), advanced control (nonlinear, predictive, adaptive [63.86]), and artificial intelligence soft-computing techniques (fuzzy control, neural networks, genetic algorithms [63.87, 88]). Control is implemented with programmable logic controllers or microcomputers. Climate controllers that use online measurements of plant temperature, and fruit growth and quality, to estimate actual transpiration and photosynthesis will be the future development. This will enable the development of closed-loop systems that use the speaking plant as the feedback for the control system and thereby result in effective control of the greenhouse climate [63.89, 90]. Effective control of the greenhouse climate must also incorporate long-term management plans to increase profitability and quality [63.91].

**63.3.2 Seedling Production**

Seedling production is one of the key technologies to grow high-quality products in fruit and vegetable production. Seedling operations such as seed selecting, seeding, irrigating, transplanting, grafting, cutting, and sticking have been mechanized or automated [63.77]. A fully automatic seedling production factory has been reported as a part of a plant factory [63.78], while a precise seeding machine which can seed in the same orientation has also been developed [63.79]. Several grafting robots and robots for transplantation from cell tray to cell tray or to pot have been commercialized. Herein, a grafting robot and a cutting sticking robot will be described as examples.

**Grafting Robot**

Grafting operations are conducted for better disease resistance, higher yield, and higher-quality products. Opportunities for the grafting operation are recently increasing, because of the agricultural chemical restrictions introduced to improve food safety and sustainable agriculture in the world. As the demand for grafted seedlings increases, a higher-performance model or a fully automatic model of the grafting robot is currently expected, while semiautomatic models have been commercialized since about 20 years ago. Grafting involves the formation of one seedling by uniting two different kinds of seedlings, using the side of the root of one seedling and the side of the seed leaf of the other. The side of the root of a seedling is called a stock and the side of the seed leaf, a scion. In order to graft a watermelon or a cucumber, a pumpkin is frequently used as a stock. The grafting method shown in Fig. 63.10 is called the single cotyledon grafting method, and is adopted as the operation process of a grafting robot for cucurbitaceous vegetables. For the stock, one seed leaf and its growing point are cut off. For the scion, the side of the root side is cut off diagonally at the middle of the hypocotyl, and the side of the seed leaf which contains the growing point is used.

Grafting operation of different kinds of plants is carried out by joining the stock and the scion using a special clip as an adhesive. Although stock seedlings and scion seedlings are hung up on spinning discs and supplied synchronously in some robot, mechanical fin-
Cutting Sticking Robot

Cutting sticking operations are often conducted in flower production in order to enhance productivity by using cuttings obtained from mother plants. Currently, humans manually stick the cuttings, however, the operation is monotonous and requires a lot of time and labor. A semiautomatic and a fully automatic chrysanthemum cutting sticking systems [63.80, 81] have been developed so far. In this section, a fully automatic system for chrysanthemum will be introduced, because it has a function of recognizing complicated-shaped seedlings by machine vision.

Robotic Cutting Sticking System. A prototype robotic cutting sticking system (Fig. 6.3.11) mainly consists of a cutting-provision system, machine vision, a leaf-removing device, and a planting device. The figure includes the latter three sections. The flow of cutting sticking operation is as follows: first, a bundle of cuttings is put into a water tank for refreshment because the cuttings are usually stored in a refrigerator for about a week until some amount of cuttings need to be prepared through picking from mother plants. The cuttings are floated on the water and spread out by adding vibrations to the tank. After refreshment in water and spread enough in a while, the cuttings are picked up by a manipulator based on information about the cut-
tions – positions and orientations from a television (TV) camera installed above the water tank.

Secondly, another TV camera (Fig. 63.11) detects the position and orientation of the cutting, which is transferred to a table from the water tank by the manipulator. The TV camera indicates the grasping position of the cutting for another manipulator, shown in Fig. 63.11. Thirdly, the manipulator brings the cutting to the planting device via the leaf-removing device. Finally, the cuttings are stuck into a plug tray by the planting device.

The leaf-removing device consists of a frame with cutters, a movable plate with rubber, and a solenoid actuator. The movable plate is driven to open and close by the solenoid actuator in order to cut lower leaves and arrange the shape of upper large leaves by chopping them with the cutters. Two identical devices are placed at an angle of 90° to cut the leaves completely since each leaf emerges at an angle of 144° from the main stem. Parts of the upper large leaves and lower petioles are cut by closing the movable plate. After this operation at the first device, the cuttings are moved to the second device and other leaves desired for removal are cut.

The planting device mainly consists of a table to place the cuttings in a row and a holding plate which opens and closes. The holding plate is driven to open and close by a motor which is mounted on the table. The table and the plate are driven in linear motion by another motor and a screw, and are rotated by a motor. A cell tray is set below the planting device. The holding plate closes after ten cuttings are placed on the table since a row of the tray has ten cells. The table rotates until it is perpendicular to the tray and moves downward. The ten cuttings are stuck into the tray together and the planting device adopts the initial position after the holding plate opens and the table moves upward.

**Machine Vision.** To pick up and transfer the cuttings, detection of the grasping point of the cutting is required. A monochrome TV camera whose sensitivity ranges from the visible to infrared regions was used with a 850 nm interference optical filter to enhance the contrast of the cutting on a black conveyor. The algorithm to detect the grasping point [63.82] is as follows: the complexity of the boundary line of the cutting on a binary image is investigated and candidate points of the stem tip are found. If only one candidate point is found in the image, the point is determined as a stem tip. When there are more than two candidate points, the complexity of the boundary line around the candidate points is detailed and points which are not adapted to conditions of the main stem are removed. The condition is that boundary lines around the stem tip have a lot of linearity. If only one candidate point remains after processing, the point is determined as the stem tip. In the case of plural points remaining, the whole boundary line of the cutting is detailed, the region of leaves is detected, and a candidate point which has a certain distance from the region of leaves is determined as the stem tip. When no point meets this condition or when more than two points remain even after the processing, the cutting is transferred back to the first stage, because it is too risky to determine the stem tip in these cases. The grasping point was defined as the position 10 mm above the stem tip. Experimental results indicated that about 95% cuttings are satisfactorily detected with no missed detection, and all remaining cuttings were transferred back.

![Fig. 63.12 Self-heading-correction mechanism and an unmanned sprayer (courtesy of Maruyama MFg., Co. Inc.) (after [63.84, 89])](image-url)
### 63.3.3 Automatic Sprayers

Chemical control is required for crop production in controlled environments, and automation of the chemical spray is desirable to minimize exposure of chemicals. Spraying robots have been commercialized so far [63.83, 92, 93]. A key technology of the robots is autonomous control of the vehicle. Figure 63.12 shows the principle of the self-heading-correction mechanism. The front axle can be turned freely around an axis A–B which is fixed to the body diagonally. Assuming that a front wheel on one side runs on a ridge (it is off course), the center of this front wheel shifts from O1 to O2. At the same time, the other front wheel moves down and back. Consequently, the resulting steering angle $\beta$ causes the vehicle to descend from the ridge, correcting its moving direction by itself. In the case where both a front and a rear wheel run on a ridge at the same time, the effect of the heading correction will be reduced because the steering angle $\beta$ may be smaller. To obtain an appropriate steering angle, the rear tread is 35 mm shorter than the front tread. An unmanned sprayer is shown in Fig. 63.12.

Another method is called electromagnetic induction type. Induction wires are laid down under ridge aisles and/or headland and a vehicle with an induction sensor detecting the magnetic field created by the wires can automatically travel along the wires. When the vehicles move to the next ridge aisle in narrow headlands in greenhouses, several methods have been reported: a pivot shaft that comes out to make the turn, four-wheel steering, an additional rail system to convey the vehicle to the next aisle, and a manual method. In orchards, automatic speed sprayers using induction wires and induction pipes were developed in 1993 and 1994, respectively. A method that uses a remote-controlled helicopter has been very popular in the fields.

### 63.3.4 Fruit Harvesting Robots

It can be said that the history of agricultural robots started with a tomato harvesting robot [63.94]. There has been much research on fruit harvesting robots for tomato, cherry tomato, cucumber, eggplant, and strawberry [63.95–100]. Vegetable harvesting robots have also been investigated, but there is no commercial robot yet. The main reasons limiting commercialization of harvesting robots are low success rates due to diversity of plant properties, slow operational speeds, and high costs associated with the seasonal affect. However, practical use of harvesting robots is expected in the future.

#### Tomato Harvesting Robot

Research on the first tomato harvesting robot started at Kyoto University in 1982 and several different types of tomato harvesting robots and their components have been developed. A cluster harvesting robot is now under development. The main components of many of the tomato harvesting robots are a manipulator, end-effector, machine vision, and traveling device, as shown in Fig. 63.13. The robot automatically travels between ridges and stops in front of a plant using photosensors and reflection plates on the ridges, which can give the location of the robot in the greenhouse. When the traveling device stops, a machine-vision system measures fruit color and location, the manipulator approaches the cluster, and an end-effector picks a fruit. After completing the operation at the location, the robot moves to the next location of the reflection plate.

#### Phytological Characteristics of Tomato Plant

Most tomato plants for the fresh market are usually grown on a vertical plane with supports or with hanging equipment until many fruit clusters are harvested. However, high-density single-truss tomato production systems (STTPS) have been reported [63.101]. In addition, an attempt was conducted to grow the tomato plant upside down on the tomato production system because of the smaller labor requirement for plant training and ease of mechanical operation. Some varieties are for individual harvesting while others are for cluster harvesting. Some varieties produce round-shaped fruits and longer fruits, depending on the season. There are also many fruit sizes. Fruit clusters are supposed to grow...
ouwards due to a growth rule, but the main stem sometimes twists, which causes random cluster direction so that tomato fruits may sometimes be hidden by leaves and stems. When a robot is introduced to the production system, it should be adaptable to plant diversity.

**Manipulator**

The basic mechanism of a manipulator depends on the configuration of the plant, the three-dimensional (3-D) positions of its work objects, and the approach paths to the objects. In the first attempt to robotize the tomato harvesting operation, a five-degree-of-freedom (DOF) articulated manipulator was used [63.98], and a seven-DOF manipulator was investigated for harvesting six clusters [63.102]. However, the Dutch-style growing system has been popularly introduced to large-scale greenhouses throughout the world, and target fruit are always located at a similar height. Therefore, a selective compliant robot arm (SCARA)-type manipulator can be used. When the fruit cluster is transferred to a container quickly, cluster swing damping is required.

**End-Effector**

The fruit cluster has several fruits and their peduncles have joints in many varieties of tomato plants. When a human harvests ripe fruit one by one in the cluster, he/she can pick them off easily by bending them at the joints instead of cutting. To harvest the fruit, several end-effectors have been developed; Fig. 63.14 shows one of them [63.103]. A 10 mm-thick rubber pad is attached to each finger plate to protect the fruit from slipping and damage. The length, width, and thickness of a finger plate are 155, 45, and 10 mm, respectively. The gripping force exerted by the finger plates can be adjusted from 0 to 33.3 N, while these finger plates grip fruits ranging from 50 to 90 mm in diameter. The suction pad was attached to the end of a rack, which is driven back and forth by a DC motor and a pinion between the finger plates. The speed and stroke of the suction pad motion are 38 mm/s and 80 mm, respectively. The suction pad can be moved forward up to 43 mm from the tips of the finger plates. The moving distance and stopping position of the pad can be detected by a rotary-type potentiometer. Two limit switches are attached to both ends of the pad stroke in order to prevent the pad from overrunning.

**Machine Vision**

A traditional method of detecting 3-D locations of target fruits is feature-based stereo vision. A pair of identical color cameras acquire images and discriminate red-colored fruits. Based on the disparity of fruits on both images, the depth of the target fruit can be calculated. Although a small error in the 3-D location occurs because of hidden parts of the fruits, the suction pad can tolerate these error. It is not easy for stereo vision to detect all fruits locations when a corresponding problem happens due to hidden fruits and many fruits in the images. In this case, a 3-D laser sensor or area-based stereo vision may help detect the fruit depths.

**Traveling Device**

Figure 63.13 shows a four-wheel-type battery car on which a tomato harvesting robot is mounted. The traveling device moves and stops between the ridges and turns at the headlands to go to another ridge. In Dutch-style large-scale greenhouses, two heating pipes are usually used. It is easy to introduce a rail-type traveling device
as these pipes can be used as rails. Rail-type traveling devices (manual or self-propelled) are already used for leaf picking, manual harvesting, spraying, and many other operations in greenhouses.

63.4 Animal Automation Systems

Automation of animal husbandry systems includes the development of environmental control systems, automated weighing and monitoring systems, and automated feeding systems.

Climate control of housed animals has an important influence on the productivity and health of the animals and therefore its control is very important [63.104]. However, this is a difficult and complicated task due to the nonlinear effects of the animals on the temperature and humidity conditions inside animal housing buildings [63.104]. In conditions where animals are housed outside, control is further complicated due to changing environmental conditions. Air-quality and environmental monitoring is important for environmental protection aspects and hence is gaining increasing attention and importance.

Devices for electronic animal identification and monitoring became available in the mid 1970s and have enabled implementation of advanced management schemes [63.105], specifically for livestock and swine management. The ISO standardization of injectable electronic transponders in the late 1990s expanded applications to all animal species [63.105]. Several sensors have been developed to provide individual animal parameters such as size, weight, and fat. These parameters are used for management decisions. The current new generation of sensors enable health and production status monitoring, both improving animal welfare and ensuring increased food quality and safety. Recent developments include acoustic passive integrated transponder tags using micro-electromechanical systems (MEMS) technology [63.106]. Tags may be used for tracing animals from growth to final processing for quality control and food security purposes [63.106].

The main expense in animal production systems is food intake. Automated feeding systems decrease production costs while ensuring that animals receive necessary nutrient ingredients. Group and individual feeding systems have been developed to measure and control food intake.

Production, health, and welfare controls are being introduced into modern farms using advanced information systems. Data from multiple sensors at the individual and group levels are taken on a daily basis for advanced monitoring and control. Various systems will be presented in the following sections.

63.4.1 Dairy

The dairy industry is probably the most automated agricultural production system, with almost all processes, from feeding to milking, being completely automated. In the dairy industry, many maintenance routines such as milking, feeding, weighing, and online recording of performance are fully automated on an individual animal basis. Optimal management is defined as producing maximum milk yield while minimizing costs. The computation and data-storage capacity of computers theoretically enable sophisticated decision-making to underpin the automated processes in order to obtain optimal individual and herd performance. These include automated feeders, sensors that measure daily activities of cows, and online automated parlor systems for recording milk production and quality. Reproduction monitoring includes systems for timing of insemination based on oestrus detection. Health care systems include detection of mastitis. The objective is to fully automate every process from feeding to milking to reduce production costs and maximize milk yield.

The physical process of feeding and recording actual feed consumption is based on feed administration of concentrates and roughage, ration composition, and feed calculation for an individual cow or a group of cows. Analysis of performance data indicates that cow performance under a uniform rationing regime is consistent in trend but varies in magnitude, and therefore an optimal feed policy, in terms of efficient rationing of concentrates, should be on an individual basis [63.107]. An alternative approach, the sweeping method, is based on average values for the herd. This can cause cows not to reach maximum milk yield because of insufficient concentrate ration or imply that excess feed be consumed since there are cows that would have reached their maximum milk yield with a smaller concentrate ration. Both result in redundant financial expense. Due to the advent of technology, the farmer is able to allocate a different amount to each cow using individual computer-controlled calf feeders [63.108] and
integrated real-time control systems for measuring, controlling, and monitoring individual food intake of free-housed dairy cows [63.109]. Individual allocation decisions are made according to each cow’s performance. Performance parameters include the individual cow’s output (milk yield and composition) and measurements of physiological variables including body composition [63.110], shape, and size. An example of a system consisting of 40 feeding cells is shown in Fig. 63.15. Each cell comprises an identification system, a fodder weight system, and an automatic opening and closing yoke gate [63.109]. Each feeding stall consists of a feeding trough, an electronic weight scale and central processing unit (CPU), identification system, presence sensor, and a cylinder with valve. All components are connected to a programmable logic controller (PLC) which processes the data and activates the electropneumatic actuators. The data is backed up to a management computer. The management computer is also used as a monitoring station and a basic man–machine interface for defining basic operations and preliminary data analysis. The specific yoke design allows the cow’s head to enter the yoke gate without enabling access to the fodder. This places the radiofrequency identification tag on the cow’s ear close enough to the antenna and simultaneously activates the proximity sensor (by the cow’s head). If the cow is allowed to eat according to the predetermined conditions, the PLC records the current scale’s weight and the yoke gate bar is lowered by the associated electropneumatic cylinder. The cow may then push its head into the fodder trough and feed. The scale measures and records the weight of the fodder at predefined intervals. Each CPU scale is connected to the PLC directly via binary code to decimal (BCD) so no time delay is caused by weight transmission. A restriction bar on the fodder trough prevents the cow from pushing its head up, thereby preventing spillage of fodder. The use of presence sensors in the yoke appeared to be very important to determine if the cow had left the yoke station. The feeding troughs were arranged in a row to enable convenient dispersal of fodder (into the containers) by the passage of a semiautomated fodder dispersal wagon.

Several methods have been developed for automatic weighing of cows. Cows are weighted as they exit the milking parlor so as not to interrupt their daily regime. The motion of cows creates measurement problems, including changes along the scale due to applied forces, crowding of cows on the scales, and significant variations between cows and between the same cow at different times of the day or on different days. Dynamic weighing of cows is a common practice in many commercial farms, achieved by filtering the measured signal and averaging it or recording the peak value as the cow transfers its weight [63.111–113] using physical mathematical models that simulate cow walking [63.114].

Milking cows is a complicated task due to the physics combined (teat treatment, control of the milking unit) and variable biological components (milk secretion, udder stimulation) including the risk of infecting the udder with pathogen microbes [63.115]. Although the first proposals for mechanical milking were presented over 100 years ago, milking machinery became common only in the early 1950s, with completely automatic milking systems being introduced in the 1990s [63.116]).

First steps in automating the milking process included detection of end of milking and automatic teat cup detaching [63.115]. Various optical, capacitive, and inductive sensors were developed to detect low milk flow, which indicated end of milking [63.117]. Mechanized stimulation of udder was achieved by using pneumatic and electronic pulsators. Continuous individual variation of vacuum level, pulse rate, and pulse rate for each milking unit was developed. Milk yield recording is implemented using tipping trays and volumetric measuring systems, with many sophisticated measuring systems to separate air from milk to improve accuracy. Automatic milking requires automatic application of teat cups. Ultrasonic sensors, a charge-coupled device (CCD) camera, and a laser are used to locate the teats to control in real time the arm to adapt to the variations in teat positions, spacings, and shape and to the motions of the cow during teat attachment. In most systems a two-stage teat location process has been applied.
First, the approximate teat positions are determined by dead reckoning using body position sensors, ultrasonic proximity sensors or vision systems. The final attachment is achieved by fine-position sensors using arrays of light beams mounted on the robot arm. Automatic checks of udder condition and milk quality include online milk analysis. Milk quality is a critical parameter both from an economic point of view and from health perspectives [63.116]. Measures include conductivity, temperature, and color of milk, integrated with yield information. Biosensors have been used to measure antibiotic residues, mammary infection components, and metabolites including the development of electronic samplers that enable real-time measurements [63.118].

Various teat cleaning systems, including brushes and rollers or separate teat-cup-like cleaning devices, have been developed. In addition, systems for cleaning the complete system (circulation cleaning, cleaning with boiling water, cluster flushing [63.116]) are applied.

Robot milking (see Fig. 63.16 for an example), introduced in the early 1990s by several commercial companies (e.g., Lely, DeLaval, GM Zenith, Fullwood Merlin), provides increased yield by increasing the frequency of milking and improved milk quality.

Automatic health measurements during automatic milking include leg health measurement and respiration rate measurement [63.120]. Lameness detection is important due to the important welfare, health, and economic problems it causes. Leg health is also measured by measuring the dynamic weight or load of each leg while the cows are weighed on scales at the exit of the milking parlor. Several techniques have been developed including pedometers, activity meters worn around the neck, force plates that measure reaction forces on walk-through weighting systems [63.120–123], and increased respiration rate measured using laser distance sensor [63.120]. Ultrasonic back-fat sensor can provide information about the health or growth status of the livestock [63.124].

Another important health measure is mastitis, a main reason for reduced milk yield and early losses in cows, caused by the biological activity of microbes. It can be detected by counting the number of somatic cells in milk. Various methods have been developed to measure it accurately using electrical conductivity measurements, body temperature, and milk temperature. Recently inline near-infrared sensors have been developed to measure milk conductivity and milk temperature of each separate quarter (a sensor is connected to each udder cup) [63.119].

The primary direct parameter to detect oestrus is concentration of milk hormones (progesterone), indicating the fertility status of the cow. However, it is commonly measured only in laboratories based on samples, although biosensors have been developed for its measurement [63.125]. Several indirect parameters have been developed into automated systems, including electrical conductivity of vaginal secretion, milk temperature, and cow behavior including cow activity measurement using pedometers, heart rate, etc. Improved measurement was achieved by combining information from several parameters (e.g., combining cow activity with milk yield, feed intake, milk temperature).

Behavior measurement has been achieved using different systems: a radar-based automatic local position measurement system for tracking dairy cows in free stall barns [63.126], global positioning systems for measuring grazing behavior (Turner et al. [63.127], video measurements [63.128], and automatic tracking systems based on magnetic induction [63.129].

Environmental control systems in the dairy industry are less common since cows are located in barns that are open, shaded or partially shaded. Systems developed include automatic cooling using fans based on online imaging systems that detect crowding (Fig. 63.16) and microclimate and gas emissions in cold uninsulated cattle houses [63.130].

Management information systems that combine herd and individual health and production param-
eters [63.131, 132] are important to ensure efficient automation. Further advances in design and management of livestock environments will require development of sustainable livestock production systems accounting systematically for the environmental benefits and burdens of the processes using a lifecycle assessment process [63.133]. Strategies will need to be developed to regulate and reduce harmful gas emissions from livestock farms and land application of manure [63.134].

### 63.4.2 Aquaculture

Physiological rates of cultured species can be regulated by controlling the environmental conditions and system inputs. This yields increased process efficiency, reduced energy and water losses, reduced labor costs, and reduced stress and disease. Automation applications include algae and feed production, feed management, environmental controls such as filtration systems, and automated air-pressure control. An intensive water-quality monitoring program includes routine sampling (twice a week) and 24 h sampling (every 3 months) of nitrogen (NO$_3$, NO$_2$), phosphate, pH, and temperature. Fish and shellfish biomass should be sampled and seaweed should be harvested [63.135, 136].

Automation usually exists in closed systems such as recirculated aquaculture systems, but it can also be applied to pond and offshore aquaculture systems. Intensive recirculating aquaculture systems (RAS) reduce land and water use at the expense of increased energy requirements for operating treatment processes to support high culture densities, often with the addition of pure oxygen (see, e.g., Fig. 63.17). The use of pure oxygen is usually expensive and requires considerable energy for dissolving in the water as well as for stripping off the carbon dioxide created by respiration. In conventional RAS design gas exchange and dissolved waste treatments (e.g., CO$_2$ stripping and ammonia removal by nitrification) are linked into one water-treatment loop. However, because excretion rates of CO$_2$ are an order of magnitude greater than ammonia excretion rates this design may result in toxic CO$_2$ concentrations. In addition, pressurized pumping and pure oxygen addition may increase the risk of gas bubble disease. Hence, low-head recirculating system that separate the gases treatment loop (oxygen and CO$_2$) from the nitrification and solid filtration treatment loop by using a high-efficiency airlift producing a bubbly flow are used [63.137]. The integrated pond system (IPS) concept suggests a novel solution for environmentally friendly land-based mariculture. The IPS recycles excreted nutrients (valuable nitrogen) through algal biofilters utilizing solar radiation for their photosynthetic processes [63.138].

Accurate size and shape information of wild and cultured fish population is important for managing the growth and harvesting process including feeding regimes, grading times, and optimum harvest time [63.139]. Information on both average weight and distribution is necessary for grading, feeding, and harvesting decisions [63.140]. Machine vision has been used to determine fish size [63.139,141], mass [63.140], color [63.141], weight, and activity patterns. The problems with image capture in ponds are the low contrast between fish, the dynamic movement of fish, and changing lighting conditions. Real-time in situ fish behavior quantification and biomass estimation has also been used for management decisions [63.142].

The cost of feed is usually the major operating cost in aquaculture [63.143]. Overfeeding results in leftovers, which leads not only to extra costs but also to poor water quality, causing additional stress and extra loads on mechanical and biofilters and oxygenation.
Fig. 63.18 Aquaculture closed system with a feeding station. Feed quantities are calculated on a daily basis to each fish tank according to fish weight, water temperature, and growth rate.

devices [63.143]. In addition feeding rhythms affect feed conversion rates and proximal composition of fish flesh. Automated feeding systems (see, e.g., Fig. 63.18) include timer-controlled feeders [63.144], demand feeders, and automated data-acquisition systems to assess fish feeding rhythm, and acoustic, photoelectric sensors to detect the turbidity of the effluent. Hydroacoustic sensors and machine-vision systems have been used to detect left-over pellets.

Future research should be directed towards engineering environmental monitoring and controlling recirculated systems, and the development of sustainable automated systems. Considering that sustainable development is probably the major challenge faced by aquaculture [63.145, 146], one should consider sustainability, which can be considered in three main categories: environmental, economical, and sociological [63.147]. Another perspective of sustainable development relates to resource utilization and external effects that are described by various indicators (mainly in physical terms [63.136]). This should include online reporting of system failures and automation of the final harvesting and grading process [63.148], thereby improving food safety and maintaining product quality.

63.4.3 Poultry

Poultry house controllers include sensors for internal and external temperature measurement, moisture, static pressure, feed lines, water consumption, and gas and vent box status [63.149, 150]. Additional automation equipment includes feed consumption monitoring equipment, bird weight scales, feed bin load sensors, gas meters, and water meters.

Physiological signals are important for health monitoring and behavior analysis. Several systems have been developed, including an implanted radiotelemetry system for remote monitoring of heart rate and deep body temperature, and multispectral image analysis for real-time disease detection [63.151]. An automated growth and nutrition control system has been developed for broiler production using an online parameter estimation procedure to model the dynamic growth of broiler chickens as a response to feed supply [63.152]. Image based bird behavior analysis can be can be used to develop time profiles of bird activity (movement, response to ventilation, huddling, etc.) as well as to compare activity levels in different portions of the house. Time profiles of bird activity can contribute to improved feeder and water design, and enhanced distribution of ventilation air to provide more uniform bird comfort [63.149,150,153].

Several mechanical poultry catching systems [63.154] have led to improvements in bird welfare in addition to manual labor reduction. Systems include [63.154]: rubber paddles that rotate onto the birds from above and then push the birds onto a conveyor belt which carries them back to a loading platform where they are deposited into crates, a hydraulic drive system that advances along the poultry house and picks up the birds with soft rubber-fingered cylinders that gently lift them onto a conveyor that transfers the birds to a caging system, and the Anglia Autoflow (Norfolk, UK) batch-mode catcher that shuttles birds from collection to a separate packing unit.

63.4.4 Sheep and Swine

Robot shearing operations have been developed and commercially applied in Australia [63.155]. The sheep is constrained with straps on a movable platform. Hydraulically position clippers using force feedback control the actual shearing of the wool. Path computations are continuously updated during the shearing process.

Several feeding systems exist in sow farming: commercial electronic feeding systems that feed one at a time by enclosing each sow as it eats, electronic sow feeding systems in loose housing environments that limit the feed ration [63.156], and a computer-controlled system that allows sows to feed from one of two feed formulations to meet their nutritional re-
requirements while satisfying their need for satiety by using bulk ingredients providing automatic body weight and average daily weight gain [63.157]. An important indicator of animal growth and health is the animals’ weight, in addition to its importance in determining readiness for market. Weighing has been accomplished using walk-through weighing based on mechanical scales and imaging systems [63.158]. Physiological variables measurements include body shape and size using image analysis [63.159]. Ultrasonic probes have been applied to measure back fat for monitoring animal growth and feeding regimes. A robotic system capable of holding a sensor and placing it on the pig while it is located in the feeding stall has been developed [63.160].

Real-time behavior and control of swine thermal comfort has been achieved using imaging systems [63.161]. Planning individual showering systems for pregnant sows to prevent heat stress [63.162] as been used in automatic shower cages to prevent waste water and improve efficiency. Automatic cleaning systems to reduce infections risks between batches of pigs has been used based on an intelligent sensor for robotic cleaning [63.163].

Recent environmental policies limiting the amount of nitrogen and phosphorus that can be applied in the field have led to the development of online analysis of pig manure systems, including mobile spectroscopy instruments in the visible and near-infrared wavebands [63.164].

63.5 Fruit Production Operations

Fruit production automated systems deal with all stages of production: growing (automated sprayers, weeders), harvesting, and post harvest operation (grading, sorting).

63.5.1 Orchard Automation Systems

Fruit production operations in orchards such as pruning, thinning, harvesting, spraying, and weeding have been mechanized and automated. Even when automation systems have been developed for the same variety of fruit tree, their components differ substantially because plant training systems, cultivation methods, climate conditions, labor conditions, and other conditions and situations differ from country to country. This section describes functions, mechanisms, and important observations of automation systems in orchards.

Fruit Harvesting Robots in Orchards

Several types of shakers are working in orange fruit orchards: trunk shake and catch, mono-boom trunk shake, canopy shake and catch, continuous canopy shake, and others. These shakers are used due to labor shortage, but the harvested fruits are only for processing into juice; they cannot be consumed in the fresh market because of unavoidable damage. Several types of orange harvesting robots that have manipulators with picking end-effectors and machine-vision systems have been reported in the USA, Japan, and European countries [63.165–169]. Figure 63.19 shows an articulated manipulator with three degrees of freedom (DOFs) mounted on the base attached to the boom. It was developed by Kubota Co., Ltd., Japan. The advantage of the articulated manipulator is its compact size when folded up in a narrow space between trees. Figure 63.20 shows a prismatic arm with three DOFs driven by hydraulic power. Citrus trees have large canopies and many branches, twigs, and leaves. Since these can often be obstacles for fruit harvesting, research on robots with more degrees of freedom has also been reported [63.170, 171]. Color cameras were often used as sensing systems to detect fruit because citrus fruit have orange colors. Fruit locations are calculated by use of stereo vision, differential object size, vision servoing, ultrasonic sensors or a combination of them [63.172–179]. Their end-effectors have the function of rotating semicircular cutters so that they can cut peduncles in various directions.

![Fig. 63.19 Orange harvesting robot (Kubota Co., Ltd.)](image-url)
Grape [63.180, 181], apple [63.182, 183], melon [63.184], watermelon [63.185], and other fruit harvesting robots [63.186] have also been studied. The basic mechanisms of the manipulators depend on fruit tree canopy size and shape. Grapevines in many of European and American countries are grown in crop rows, but those in Asian countries are grown on a trellis training system due to different climate conditions. Melons and watermelons are grown on the ground. There is research on fence-style training systems for orange trees [63.187] for higher-quality products. This approach of changing the training system takes a horticultural approach to accomplish a higher rate of success for harvesting robots. Since the harvesting operation is usually conducted once in a year in orchards, during a short period, a robot which can only harvest fruits is not economical. Therefore, other operations such as thinning, bagging, and spraying are needed for the orchard robot. Some of these functions are accomplished by replacing end-effectors and software [63.188].

Automation of Spraying and Weeding Operations

Control of disease, insect pests, and weeds is an essential operation to gain a stable high yield of crops and high-quality products. This operation includes biological, physical, and chemical methods. Chemical spraying is widely used in agricultural production environments. Today, technologies with high accuracy to spray only the necessary parts of the plant using a minimum amount of chemicals are required to protect workers as well as the environment.

A nozzle-positioning system for a precision sprayer was studied with a robust crop position detection system at Tohoku Experimental Station, Japan [63.189] under varying field light conditions in rice crop fields. The data from a vision sensor was transmitted to a herbicide applicator that is made up of a microcontroller, with slidable arms coupled with spray nozzles. Nozzles were driven to the optimal positions. The system was tested to evaluate its performance. It had high enough accuracy for use in Japanese rice crop fields. A fluid-handling system to allow on-demand chemical injection was developed for a machine-vision-controlled sprayer. The system was able to provide a wide range of flow rates of chemical solution [63.190].

Wiedemann et al. [63.191] developed a spray boom that could sense mesquite plants. Sprayers were attached to tractors and all-terrain vehicles. Controllers were designed to send fixed-duration voltage pulses to solenoid valves for spray release through flat-fan nozzles when mesquite canopies interrupted the light. The levels of mesquite mortality achieved were equivalent to those achieved by hand-spraying by ground crews.

The speed-sprayer (SS) has been widely used in orchards and its autonomous control is a main theme in the automation of the spraying operation. The electromagnetic induction type and pipe induction type were commercialized in 1993 and 1994 [63.192, 193]; both types require induction wires or pipes on the ground, underground, or above ground at 150–200 cm height and between tree rows. Induction sensors, safety sensors (ultrasonic sensor, touch sensors), and other internal sensors are installed in the unmanned SS, and autonomous control is conducted with fuzzy theory. Another method of SS control with genetic algorithm and fuzzy theory using GPS has been reported [63.194].

Figure 63.21 shows a multioperation robot with a three-DOF Cartesian coordinate manipulator and an end-effector [63.195]. When an end-effector shown in Fig. 63.22 is attached to the manipulator, it can weed...
on the ridge between crops. Color images of the weed are fed to a computer from a color camera and the three-dimensional location of the weed is calculated using a binocular stereo method. Weed detection is conducted using color or texture difference between weed and soil or crops \[63.196–198\]. The end-effector was a weed knife with a spiral shape (4 cm diameter). This robot can also be a leaf-vegetable harvesting robot or a transplanting robot when the end-effectors were replaced \[63.186\].

### 63.5.2 Automation of Fruit Grading and Sorting

Because of the ever-growing need to supply high-quality food products within a short time, automated grading of agricultural products is getting special priority among many farmers associations. The impetus for these trends can be attributed to increased awareness of consumers about their health well-being and a response from producers to provide quality-guaranteed products with consistency. It is in this context that the field of automatic inspection and machine vision comes to play the important role of quality control for agricultural products \[63.184–188\]. Unlike most industrial products, quality inspection of agricultural products presents specific challenges because nonstandard products must be inspected according to their appearance and internal quality, which are acceptable to customers only for nondestructive methods \[63.199\]. Several sensors have been developed and applied for internal quality determination, including sugar content, acidity, rind puffing, rotten core, and other internal defects \[63.190–194\].

#### Fruit Grading System with Conveyors

Figure 63.23 shows an automated inspection system for quality control of various agricultural products, with fruits and vegetables being the main ones. As a representative of other agricultural products, discussion in this section is focused mainly on the orange fruit, a major agricultural product inspected by this system. The main components of the system for automated inspection and sorting can be outlined as follows:

1. Product reception from supplier
2. Container unpacking and dumping of products
3. Feeding of products to the conveyor line
4. Inspection for internal and external conditions and defects followed by assignment of quality rating
5. Weight adjustment and release of the inspected product into packing box
6. Labeling of grade and size using an inkjet printer
7. Box closure and sealing
8. Box transfer onto palette and loading ready for marketing

These features are integrated into an operational line that combines advanced designs, expert fabrications, and automatic mechanical control with the main objective of offering the best visual solutions and stable quality judgment.

**Illumination and Image-Capture Devices**

Illumination is one of the most important components for the machine-vision system to inspect products, because it determines the quality of images acquired, especially for glossy products whose cuticular layers are thick. Polarizing filters are sometimes used in front of lighting devices and camera lenses to eliminate halation on the acquired images [63.195]. A color CCD TV camera is often employed to sense light through photosensitive semiconductor devices, and the CCD array data is transferred by progressive scan mode to the frame storage area, representing an image of the scene [63.196]. The TV camera is equipped with one chip that transfers red–green–blue (RGB) analogue data and is set at a shutter speed of 1/10 000 s during inspection because line speed is usually 1 m/s. Image-capture boards with 8 bit level resolution and spatial resolution of about 512×512 pixels have been used to store and digitize video signals and output the data to computer memory for analysis or display on the monitor. Recently, a special image-acquisition device, a universal serial bus (USB) or a local-area network (LAN) is often used between TV camera and personal computer (PC) instead of the image-capture board, enabling image processing to be performed within 10–30 ms.

**Product Reception and Forwarding**

The first step in the inspection procedure starts at the receiving platform, situated on the ground floor. Agricultural products are packed into containers by the farmers and delivered to the inspection factory in trucks. A folk lift is used to unload the containers on one pallet and deliver them to the depalletizer device that separates the containers automatically so that they are fed one by one to the conveyor, which propels them to the upper floor, where the main inspection line is located. The depalletizer has a capacity to handle 1200–1400 pallets per hour. After depalletization, the containers are handled by the dumper machine. The dumper is an automated machine that turns and empties the containers gently and then spreads the fruit on a belt conveyor. Using specialized rollers fruits are singulated so that they are fed singly to the roller-pin conveyor before processing. To acquire a complete view of the fruit the roller pins have been designed so that the fruit is always positioned at the center point.

**Internal Quality Inspection**

The first stage in the inspection sequence is to determine the sugar and acid contents using a near-infrared (NIR) inspection system. A special sensor determines the sugar content (brix equivalent) and acidity level of the fruits from light wavelengths received by specific sensors after light is transmitted through the fruit. The sensor photoelectrically converts the light into signals and sends them to the computer unit, where they are processed and classified. In addition, the internal fruit-quality sensor measures the granulation level of the fruit, which indicates its internal water content. Next, the fruit is conveyed to the x-ray imaging component, which inspects for biological defects such as rind puffing and the granulation status of the juice sacs. X-ray imaging operates by transmitting x-rays released from a generator through the orange fruit. The emitted optical x-ray image is relayed to the x-ray scintillator, an optical device that consists of a thin coat of luminescent materials through which x-rays are converted into the visible light of a normal image. The resulting image is captured by a monochrome CCD camera and copied to computer memory through an image-capture board.

**Image Analysis**

At the next operation, the fruit is conveyed to the third inspection stage where the main image processing and grading takes place using factory automation computers (Fig. 63.23). Six CCD cameras set in random trigger mode acquire images of the fruits as they are conveyed at constant speed. Firstly, two side cameras on the right side, placed equidistance from the central position of the fruit, capture images of the right side of the fruit. Next, two side cameras on the left side, again placed equidistance from the central position of the fruit, capture images of the left side of the fruit. Finally, the fruit is then spun through 180° around a horizontal axis by mechanically controlled roller pins, which facilitates the...
acquisition of another image of the lower surface by a sixth camera. Images are captured by CCD cameras after a trigger signal is received through the digital input/output (DIO) board. Sensors, wired to a sequencer box, are used to track the fruit position and the output is relayed to the DIO board from where the program reads the 8 bit output data.

Image processing is then executed and the following features are inspected:

1. Size (maximum and minimum diameter, area, and extrapolated diameter)
2. Color (color space based on hue, saturation, intensity (HSI) values and RGB ratios)
3. Shape (perimeter $L$, $L^2$/area, inflection point of outer surface, and center of gravity)
4. Bruise (based on intensity of blue color level and summation of color levels for blue, and R–G derived images)

Results of processing are written to a shared memory area using a memo-link from where a judgment PC makes decision about the quality of the fruit. Grading for quality is assigned by ranks of between four and six. Graded fruits are conveyed to the weight adjustment machine, which controls the total weight of oranges to be packed in a box according to preset values. Between four and eight weight rankings of fruits are used to fill different pack boxes. An automatic barcode labeler then prints the grade and size outputs on the box using an inkjet printer before the packing box is closed by the case-sealer machine. At the end of the product inspection line a robot-controlled palletizer completes the process by arranging the boxes onto palettes ready for onward loading onto trucks and transport to consumer markets.

**Data Maintenance**

An important feature of the grading system design is that it is adaptable to the inspection of different products such as potato, tomato, persimmon, sweet pepper, waxed apple, and kiwi fruits with adjustments only to the processing codes. Several lines for orange fruit inspection combined with high conveyance and high-speed microprocessors enable the system to handle large batches of fruit product at high speeds. Apart from quality inspection another objective of this system is to gather data about product performance. Identification of certain defects and counts can lead to the discovery of the cause and its severity. All data from receipt of fruits at the collection site through the analytical processes, packing, and shipping is stored in an office computer connected through a local-area network (LAN) to the corresponding factory automation PCs. Experienced personnel manage the data, based on which day-to-day operations can be monitored remotely. By making product performance records available on the Internet it will be possible to monitor performance online and provide a useful service to the customers. All in all, the customer of a product is the final judge of its quality. Therefore, keeping internal standards and specifications in line with customer expectations is a priority that is achieved through good relationships and regular communications with the customer.

**Fruit Grading Robot**

Based on the technologies of the grading system described in the previous section and robotic technologies, a fruit grading robot as shown in Fig. 63.24 was developed in 2002. This robot system has two three-DOF Cartesian manipulators, 16 suction cups as end-effectors, and 16 machine-vision systems consisting of 16 color TV cameras and 36 lighting devices. This can be applied to tomato, peach, pear, apple, and other fruits.

Operation flow with this grading system is as follows:

1. When products are received, four blocks of containers (a block consists of ten containers) are loaded on a pallet.
2. A block of the containers is lifted up to the second floor, where the main parts of the grading system work, and a container separator sends containers one by one to a barcode reader.
3. After obtaining information from each barcode attached to a container, the container is sent to a robot, the fruit providing robot.

4. The robot sucks fruits up by using suction pads and moves them to a halfway stage.

5. Another robot, the grading robot, picks fruits up again from the halfway stage and bottom and side images of fruits are acquired by TV cameras during transferring fruits.

6. The robot transfers them to trays on a conveyor line and a top image of the fruit is acquired in a camera box.

7. After appearance inspection, internal conditions and sugar content are inspected by an infrared analysis sensor.

8. Fruit that pass the internal quality sensor box are packed into a corrugated cardboard box by a packing robot based on their grading results. Grade, size, and name of fruit variety are printed on the box surface by an inkjet printer and the box is closed and sealed.

9. Finally, the boxes are transferred onto palettes and are loaded into a truck for marketing.

Figure 63.25 shows the actions of the two manipulators: the fruit providing and grading robots. A container in which \(8 \times 6, 6 \times 5, 6 \times 4\) or \(5 \times 3\) fruits are filled is pushed into the working area of the providing robot by a pusher (1). The providing robot has a three-DOF Cartesian coordinate manipulator and eight suction pads as end-effectors. The robot sucks eight (maximum) fruits up (2) and transfers them to a halfway stage, spacing fruit intervals in the \(y\) direction (3). Two providing robots independently work and set 16 (maximum) fruits on a halfway stage. A grading robot which consists of another three-DOF manipulator (two prismatic joints and a rotational joint) and 16 suction pads sucks them up again (4) and moves them to trays on a conveyor line. Bottom images of fruits are acquired as the grading robot moves over 16 color TV cameras. The cameras and lighting devices turn down 90° following the grading robot’s motion (5). Before releasing the fruits to trays on the line, the TV cameras acquire four side images of fruits as they rotate through 270° (6). After image acquisition, the robot releases the fruits into trays (7) and a pusher pushes 16 trays to a conveyor line (8).

This grading robot’s maximum speed was 1 m/s and its stroke was about 1.2 m. It took 2.7 s for the robot to transfer the 16 fruit to trays, 0.4 s to move down from the initial position, 1 s to move back from releasing fruits, and 0.15 s for waiting. Total time was 4.25 s to move back and forth for the stroke. This makes this robot performance approximately 10 000 fruit/h. In this system, four blowers with specification of 1.4 kW, 3400 rpm, 38 kPa, 1.3 m³/min displacement were used for two providing robots and a grading robot. About 30 kPa vacuum force was suitable for sucking peach fruit, while 45 kPa was used for pear and apple fruits and no damage was observed even after sucking peach fruits twice. The tray has a data carrier (256 byte EE-PROM), and grading information of each fruit is sent from a computer to the data carrier through an antenna after image processing. A conveyor line transfers the trays at 30 m/min [63.197].

### 63.6 Summary

Despite the problems in introducing automation into agricultural production systems many automation systems have been developed and are commonly applied in agricultural operations. Automation has increased the efficiency and quality of agricultural production systems. However, automated or semiautomated farming is far from a reality in many parts of the world. Due to
cheap labor in third-world countries, much of the work on farms is still performed manually. Despite the large capital investment needed to purchase the equipment, automation will probably be introduced also into these countries to provide the needs for increased production and land efficiency.

In industrialized countries the production trend is towards large-scale farms and hence automation will be advanced and commercialized to make this feasible. Farmers must produce their food at competitive prices to stay in business and automation of farming technology is the only way forward. With the improvement of sensors and computers, and decrease of automation equipment costs, this is becoming feasible and more systems will be introduced. The current century will probably see significant advances in automation and robotization of farm operations. The future farm will include integration of advanced sensors, controls, and intelligent software to provide viable solutions to the complex agricultural environment.

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