Machine Vision Based on Optical Properties of Biomaterials for Fruit Grading System

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It is known that biomaterials have unique characteristics in their color, shape, size, spectral reflectance, and biological structure which are different from industrial materials. Specific machine vision designs are often required for constructing inspection, monitoring, measuring, or production systems to handle the biomaterials. In this presentation, cuticular layers on fruit surfaces are in focus and a direct lighting device with a polarizing filter, which was developed for a fruit inspection system is introduced, because illumination is one of the most important components. Since the biomaterials have various reflectance in different wavelength bands, characteristics of light from gamma ray to terahertz were described. In the visible region, there are many types of light sources, which have different properties on luminance, lumen maintenance, color rendering, color temperature, life, and cost. A high quality image acquisition requires a proper light source selection. Fruit grading facilities are places where the largest number of machine vision systems are practically used in agricultural fields. In this paper, a conventional fruit grading machine and a fruit grading robot with machine visions are introduced. In addition, a contribution of the imaging technologies of the grading systems to the food traceability system is explained.

Keywords: direct lighting, fruit grading system, polarizing filter, traceability

INTRODUCTION

Machine vision today is one of the most essential sensors in many kinds of inspection systems. There are some grading facilities where more than 6 machine vision systems are working for an individual fruit on each line to measure the fruit size, color, shape, and defects. Since the images from the machine vision contain a lot of information and recent technologies on electronics and mechatronics are quickly progressing year by year, wider use of the machine vision systems is expected in other bioproduction operations.

When a machine vision system is constructed, the lighting device is a key component. Many types of imaging techniques and devices have been developed so far not only in visible region but also in X ray, UV, and infrared regions, because bio-products have many different characteristic phases in those regions. The latest technologies reached terahertz (THz) imaging by development of new light sources and detectors (Hu and Nuss, 1955; Kawase et al., 2003) and studies were started applying to bioproduction field by use of these new devices. In addition, nuclear magnetic resonance (NMR) technology has been also applied to bioproducts (Chen et al., 1989; Song and Litchfield, 1990; Wang et al., 1988). In this presentation, the characteristics of the various lights
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Bioproducts have unique characteristics in appearance, in many wavelength bands, and in structural properties on their surfaces. With their uncertain shapes, the cuticular layers sometimes cause halation and wall reflection on fruit surfaces in images. Here, the problems of imaging the bioproducts are described and a method to avoid these problems is explained. Although the images from the machine visions usually have only two dimensional information, the depth (three dimensional information) is often needed for robotic applications with machine visions. As examples of the machine vision systems used in agricultural fields, fruit grading systems are introduced, and a contribution of the imaging information to the food traceability system is explained.

MATERIALS

Characterization of lights from gamma ray to terahertz

Figure 1 shows types of lights and electromagnetic waves. The righter position the light shifts, the shorter the wavelengths is and the higher the frequency is. Gamma ray has a transmitting ability so that it's imaging technologies are known in a medical use as PET (Position Emission Tomography) or SPECT (Single Photon Emission Computed Tomography), which can diagnose human body's blood flow and detect an earlier stage of cancer. The images are different from the ones of X ray CT or MRI based on the difference of electromagnetic characteristics. X ray can also transmit most objects except water and metals and its imaging devices are very popular for our routine health check up. In bioproduction, many of X ray cameras or sets of scintillators and monochrome cameras are often used for nondestructive internal qualities of fresh fruits and for food inspections today.

Ultra violet (UV) light is classified into three types in order of wavelength: UV-C (100–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm). They say that the UV-C light has disinfectant effects and reduces the amount of bacteria, viruses and mold. It is well known that the UV-B light causes sunburn, while they say that it creates vitamin D in our bodies. The UV-A, which is called “the black light” attracts insects, because many insects have sensitivities in this range. It is easy to buy this UV-A light source at electric or electronics retailers. The UV-A also makes our skin suntan by creating melanin. When those lights come from the sun, the UV-C light and some of the UV-B are not supposed to reach the earth surface due to absorption of the ozone layer. However, UV-A and the remaining of UV-B (more than 290 nm) lights actually affect us. In the UV-A range, some flower petals have high reflectance to attract insects and some bioproducts containing fluorescent materials often fluoresce in the visible region by an excitation of this light. This

![Fig. 1 Frequency map for electromagnetic waves.](image-url)
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often helps detect defects of fruits, plants, and meats (Bodria et al., 2002; Kim et al., 2001; Kim et al., 2004).

Visible (VIS) light (400–700 nm) is the most commonly used for imaging among the many electromagnetic wave ranges. Many TV cameras and monochrome cameras are already practically used for measurement of fruit and vegetable size, color, shape and defect in grading systems and for an inspection of germination in cell trays. Parts of plants with chlorophyll have an absorption band at around 670 nm in spectral reflectance. The red color and blue color lights are essential for plants to healthily grow through photosynthesis, that means that most leaves show green color which is reflected as an unnecessary color component for the plants.

Infrared (IR) region is often divided into two: near infrared (NIR: 700–2,500 nm) and far infrared (FIR: 2,500 nm–30 μm). Most bioproducts have higher reflectance in the near infrared region than in the visible region and many absorption bands of H2O at 970, 1,170, 1,450, 1,950 nm, etc. in this region. This near infrared light is often used to nondestructively inspect sugar contents and internal defects in fruits (Kohno, 2003; Lu and Ariana, 2002; Sagara, 1998). Measurement of nitrogen and soil organic matter in the field is also done by this light (Shibusawa et al., 2001; Shibusawa et al., 2002). It is well known that far infrared light penetrates bio-products deeply, which has effectiveness to heat and cook them well. Charcoals, woods, ceramics and others can be materials to radiate the far infrared light.

A region between far infrared and millimeter wave that is called terahertz region (THz: mainly the sub-millimeter wave region) was not frequently utilized yet, because there was no convenient method to generate it. Recently, however, a compact light source of the THz was developed (Kawase et al., 2002; Mitteleman, 2003) and studies on application of the THz to bioproducts started (Ogawa et al., 2004). The THz wave has both characteristics of convenience to handle light and transmittance of radio wave. This implies that although the radio waves have difficulties to be concentrated by lenses and to be reflected by mirrors, the THz wave can be concentrated into a spot whose diameter is several hundred μm. It is reported that the THz wave has absorption bands for chemicals and other materials and that a rapid method to inspect DNA, chemicals and nutrition is expected (Brucherseifer et al., 2000; Walther et al., 2000; Ferguson and Zhang, 2002; Watanabe et al., 2003; Shibuya et al., 2005; Yamaguchi et al., 2005). Besides, the transmittance ability of the THz wave is similar with that of the X ray, but it is said that there is nothing to be exposed to its radiation.

Spectral reflectance of plants

Distinctive optical properties of biomaterials are the most important parameters for designing a machine vision in bioproduction. Figure 2 shows the typical spectral reflectance of parts of plants in the region from near UV to NIR. In the VIS region, an absorption band is observed at around 670 nm when the parts of the plants have chlorophyll in the figure as described before. The fruit and flower colors depend on the plant varieties and growing stages.

The reflectance of some flowers such as tomato or cucumber in the UV region is of interest, because the percentage of reflectance is high near 300 nm. Based on this observation, it is thought that the sensitivity of some insects’ vision includes the UV region. It is considered as the co-evolution with those flowers and it is interesting to know about attractors such as nectar guide on flower petal and pheromone.

In the NIR region, there are many absorption bands due to water at 970, 1,170, 1,450, and 1,950 nm, and all parts of the plant have higher reflectance here than in the VIS region. The absorption bands at 970 and 1,170 nm are not due to flower petals and leaves but to fruits and stems. This absorption depends on the thickness of the object, since the absorption bands at 970 and 1,170 nm appear when measured with several layers of leaves and flower petals. These wavelengths can be used for discriminating them from the other parts of the plant in the NIR region.

From the Fig. 2, it is observed that there are two fruit categories: one has higher reflectance
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in the region from 700–1,400 nm (cucumber, eggplant, apple, peach, pear, persimmon, oranges, and so on) and the other has a lower one (tomato, grape, strawberry, pepper, and so on), while reflectance of most of leaves has about 50% in the region (Kondo, 1988). The reason why there are two types of fruits is not reported yet, but it is considered that it may be connected with the moisture status on the fruit surfaces.

Cuticular layer and its influence on image

Many bioproducts have glossy surfaces because of the cuticular layers. This may sometimes become a difficulty to acquire high quality images of bioproducts. Figure 3 shows a sample of microscope image of an apple fruit surface structure. It consists of the outer cuticular layer, epidermal cells, and inner parenchymatous cells. The cuticle is a transparent layer through which water cannot pass and is made from cutin and wax, which makes it glossy. Leaves, stems, fruits, and seeds have the layers, which play an important role to prevent water from passing through their surfaces and evaporating. The development of this cuticular layer depends on plant variety, organ, maturity, environmental condition of cultivation and other factors. It is said that this layer grows during dry season and is eroded away by rainfalls; and that degree of its gloss has some relation with fruit freshness. There is a case where fresh eggplant fruits with a defect have less glossy surfaces even when still on their mother plant. It seems that the firm and low quality fruit flesh is greatly affected through slow cell division speed caused by some physiological factors.

Since most of plant parts except root have glossy cuticular layers, their images should be ac-

![Fig. 2 Spectral reflectance of plant parts.](image)

![Fig. 3 Cuticular layer of an apple fruit.](image)
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quired so carefully that any halation and surrounding reflection may not occur on their surfaces in the images. Figure 4 (left) shows an apple image with halation when 4 halogen lights radiated with diffusers. Figure 4 (right) is an image of wall reflection when a dome with the same 4 halogen lamps was used. The pixel data occupied by the halation or the surrounding reflection lose object information. It is obvious that irregular fruit shapes often make unexpected halation occur at local places or unevenness of illumination may be found on the fruit surfaces, even when illumination conditions are perfectly adjusted for the fruit variety. Number of halation sometimes exceeds number of light sources due to the irregular shape as shown in Fig. 4 (left). In Fig. 4 (right), the dome walls are reflected on the eggplant surface, because they are close enough to the fruit to be shown on surface. It is desired that there is nothing around the objects of bioproducts with gloss surfaces when their images are acquired. To eliminate the halation and the surroundings reflection is the most important subject for a construction of a machine vision system as well as to uniform the illumination condition for the fruit variety.

LIGHTING DEVICES AND METHODS FOR MACHINE VISION

Indirect lighting device

As one of the conventional methods for lighting fruits and vegetables, a dome in which several lamps are held has been popularly used (Fig. 5 (left)). This is called an indirect lighting method, because light from the halogen lamps reaches fruits not directly but after reflecting on the dome walls. This method enables cheap and compact lighting system, but the wall reflection is not avoidable. Another method to use diffusers in front of lamps as Fig. 5 (right) causes halation on fruit surfaces as shown in Fig. 4.

Direct lighting device

Figure 6 shows a lighting device (Direct Light: DL) manufactured for a purpose of eliminating the halation on fruit surfaces. It mainly consists of a halogen lamp with a mirror, two heat absorption filters, a polarizing filter (PL filter), and a fan. Images acquired under the DL have no halation and no surroundings reflection due to using a set of the PL filters in front of a halogen lamp and

![Fig. 4](image)

**Fig. 4** Halation (left) and surroundings reflection (right: white walls are reflected) on surfaces.

![Fig. 5](image)

**Fig. 5** A dome for fruit illumination (left) and indirect lighting method (right).
A direct lighting device (DL).

A key technique of DL development was how to protect the PL filter in front of the halogen lamp, because the PL filter usually start melting at 60°C. The two heat absorption filters for different wavelength bands were used and 22 l/min cold air was blown to the PL filter from a compressor. About 10 cm diameter fruits such as apples, pears, peaches can be uniformly illuminated by 3 or 4 DLs with about 20 cm distance. Compared with the indirect lighting devices, this makes higher performance of color reproduction because of no wall reflection and halation.

A 12 V, 50W halogen lamp with 38° radiation angle, 3200 K color temperature, and 4,000 h life was set in the DL. There are many other types of lamps such as incandescent lamp, fluorescent lamp, LED, HID (high intensity discharge) lamp, etc. It is important to select an appropriate lamp based on the optical properties of object and on its own purpose, because the properties on luminance, lumen maintenance, color rendering, color temperature, life, and cost vary depending on the lamp as shown in Table 1.

MACHINE VISION SYSTEMS OF FRUIT GRADING SYSTEMS

Fruit grading machines

There is no doubt that it is in fruit grading facilities where the largest number of machine visions are practically used in the agricultural field. Figure 7 shows a typical Japanese fruit grading system in which 6 color TV cameras per grading line to measure size, color, shape, and surface defects on all fruit sides (Njoroge et al., 2002). A set of the three DLs are used at each image acquisition stage. Besides, NIR inspection system and X-ray imaging system are also often installed on every grading line for detecting internal defects such as sugar content, acidity, and rind puffing of orange fruit. This conveyor has a function of 180° inversion of fruit to inspect not only a top and 4 side images but also a bottom image. Since it conveys fruits at a speed of 1 m s⁻¹, 5 or 6 fruits per second are inspected. Outputs from the three color cameras are inputted to a PC and their images are processed to extract features. The data of the extracted features are sent to a host PC and are used for sorting fruits. In addition, the data from each fruit are accumulated into a database in the grading system and can be utilized for a traceability system to consumers and to distributors as well as for farming guidance to producers. Here, it is possible to replace the four image acquisition stages of the DLs into the two domes. The domes can be set before and after the 180° fruit inver-

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sion so that the inspection line becomes short, however, the halation and surroundings reflection may occur on irregular glossy fruit surfaces.

**Fruit grading robots**

Fruit grading robot systems with machine visions for apple, pear, peach, and tomato has been commercialized in Japan. Figure 8 shows a grading robot transporting tomato fruits from containers to trays on a line. It has two Cartesian coordinate manipulators, which can suck 16 fruits up at a time. Sixteen TV cameras and 34 DLs are installed to the robot system for an inspection of all sides of fruits as the robot’s vision. The robot’s vision acquires a bottom and 4 side images of each fruit during the manipulator motion from containers to trays (Kondo, 2003). The cameras and the DLs can turn 90° to take the bottoms and sides of the fruits into their views. The manipulator’s cycle time was about 4.2 s to provide the 16 fruits to the trays on a line. This robot system enables accurate information to be extracted from the fruit images, because it can precisely rotate each fruits by the manipulator compared with roller pin conveyor in Fig. 7.

**Information for traceability system**

Both fruit grading systems described above can extract fruit size, color, shape, and defect data from images, which are stored in a database in a computer. The data could be used for traceability between harvesting and distribution stages. The graded fruits are packed into boxes to which product-IDs (number assigned to product package) are attached. After grading, a packing robot could be used instead of conveyor system in order to improve traceability. Figure 9 shows a system where grading and packing robots are used to provide traceability up to production data.

Containers from producers have individual barcodes, which have data of producer ID, field
ID, fruit variety and number of fruits in the containers. Those data of each fruit from the grading robot are stored in a PC automatically and the data are immediately sent to each IC memory in tray through an antenna and a ROM-writer. Based on the data, each fruit in tray is sorted and is packed into a box. In the box, the fruit position can be still corresponded to the fruit data stored in order of the position in the PC as long as the fruit position is kept. All the data of the fruit are accumulated in a traceability database with linkage to other production data. In case checking the data of a fruit in a box at the distribution or consumption stage is needed, it is possible to trace all the data up to the production stage by typing product ID and the fruit position in the box. It is obvious that relation between farming operations and grading data, which are accumulated in the database every year can be used as farming guidance to achieve precision agriculture.

CONCLUSION

Many machine vision systems of various cameras are now working practically in the fruit grading facilities. In other bioproduction operations such as field management, seedling production, crop management, and harvesting, the machine visions are one of the most important sensors to collect information from biomaterials. They can contribute to all the stages from production to consumption not only for labor substitution, market value enhancement based on uniform product quality, fair payment, and farming guidance to producers but also for the food traceability database to distributors and consumers.

REFERENCES

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