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과일의 품질 평가를 위한 레이저 비전 응용

조용진 · Young J. Han* · 이종환*
한국식품개발연구원, *미국 클렘슨대학교 농업생물공학과

Feasibility of Laser Vision for Evaluating Fruit Quality

Yong-Jin Cho, Young J. Han* and Jong-Whan Lee*
Korea Food Research Institute
**Department of Agricultural and Biological Engineering, Clemson University, USA*

Abstract

A laser vision system was set up to evaluate firmness of apples nondestructively. A He-Ne laser at 632.8 nm wavelength and a diode laser module at 685 nm wavelength were used as a light source. Combinations of neutral density filters were used to modulate the optical output of the laser light source. A series of experiments was conducted using two varieties of apples (Golden Delicious and Rome). Eight features of interest were derived from the laser images to estimate the fruit firmness using multiple regression analysis. The estimated and measured firmness were compared statistically to evaluate effects of different laser wavelengths, output power levels, incident angles and sample orientation on fruit firmness measurement. The laser incident angle of 15 degrees was recommended for capturing laser images of apples without a specular reflection or undesirable glare. Sample orientation did not significantly affect but laser wavelengths and optical power levels did the system performance. Laser image analysis was able to estimate apple firmness from the derived laser image features.

Key words: laser vision system, image analysis, firmness, apple

Introduction

Firmness is one of the few internal quality factors that consumers can use to evaluate fruits before purchase. Firmness is also used as an indicator of fruit maturity by growers and packers. If packers could sort apples rapidly and nondestructively by firmness, they could produce a more uniformly ripe pack for the fresh market. In general, firmness of an apple is greatest at its harvest and decreases gradually during storage as it becomes more mature. Overripe and damaged apples become relatively soft and easy to be punctured.

Several studies have examined relationships between maturity of fruits and their optical characteristics (Heron and Zachariah, 1974; O'Brien and Sarkar, 1974; Goddard *et al.*, 1975; Moini and O'Brien, 1978). Most of these studies utilized a spectrophotometer or a light-sensitive cell (such as photodiode, photomultiplier, or photovoltaic cell) as light sensors to quantify light reflectance, transmittance, or absorbance characteristics. These sensors evaluate only a few locations around the fruit, or estimate overall average light reflectance from the entire fruit surface. Recently, machine vision/image processing technology has been used to evaluate light reflectance from surfaces of fruit locally and globally (Sarkar and Wolfe, 1985a, 1985b; Slaughter and Harrel, 1987; Wiggers *et al.*, 1988; Miller and Delwiche, 1989; Shearer and Payne, 1990; Varghese *et al.*, 1991; Choi *et al.*, 1995). One limitation of these techniques is that the usual machine vision system relies on the surface or near-surface optical reflectance properties of the fruits.

Duprat *et al.*, (1995) used a low power laser diode module (1 mW at 670 nm) as a light source to a black-and-white vision system to evaluate the

Corresponding author: Yong-Jin Cho, Senior Research Scientist, Korea Food Research Institute, P.O. Box 2, Pungdang-ku, Songnam-si 463-050, Korea

apple ripeness. The resulting spot size of the laser light was measured as an index of apple firmness. They showed that the spot size in laser image increases with ripening of the apple, and reported a nonlinear negative correlation between the spot size and the firmness. Tu *et al.*, (1995) also used a low power diode laser beam (3 mW at 670 nm) as a light source to a color vision system and analyzed the scattered reflection of the laser light to monitor the maturity of the fruits such as tomatoes and apples. The total number of pixels in the image exceeding a threshold value was taken as a maturity indicator. Their results showed a potential for using a laser beam as a light source to classify fruits according to quality. Using a laser beam as a light source can provide a new dimension to the machine vision technology in that sub-surface properties underneath the fruit skin can be analyzed using a regular color vision system.

The specific objectives of the research were to integrate a state-of-the-art machine vision system with various types of laser beams as a light source and to analyze the characteristics and feasibility of the laser beams as a light source by evaluating effects of different laser wavelengths, output power levels, incident angles and sample orientation on firmness measurement of apples.

Materials and Methods

Laser Vision System

The laser vision system consisted of a laser light source and laser holders, color and monochrome cameras, a microcomputer with a frame grabber board (Coreco Oculus-TCX, 4MB), image display monitor (Sony Model PVM-1271Q), sample holder and tabletop stand. Color images were captured by a Sony DXC-151A RGB Color Camera. Monochrome images were captured by a Panasonic WV-CD500 monochrome CCD camera. A Fujinon-TV 12.5-75 mm F1.2 zoom lens and two close-up lenses (Tiffen Co., diopter +1, +2) were used to adjust the field of view.

The specifications for two lasers used in this study are summarized in Table 1. The laser heads were secured onto a porcelain base support stand by two adjustable angle clamps. Apple samples were positioned on a plexiglass sample holder and placed on a 15.2 cm by 15.2 cm stainless steel positioning lift so that the distance from fruit samples to the camera can be adjusted. Image analysis algorithms were developed using the macro language provided by Optimas 5.2 Windows-based image analysis software.

Table 1. Specification of the two laser light sources

Manufacturer Model Number	Melles Griot 05-LHP-981	Melles Griot 56-DIB-122/P1
Wavelength	632.8 nm	685 nm
Minimum Output Power	16 mW	20 mW
Beam Diameter	1.47 mm	3×1 mm
Beam Divergence	1.40 mrad	0.4×1.2 mrad
Operating Voltage	2550 V DC	5 V DC
Operating Current	7.0 mA	60 mA

Various power levels of a laser light source were achieved by modulating the laser output with neutral density filters. In this study, a set of seven precision metallic neutral density filters (Melles Griot, Model 03-FSG-013) was used. The actual output power levels before and after the neutral density filters were measured by a digital laser power meter (Coherent Instrument Division, Model Laser-Mate-Q).

Sample Preparation and Firmness Measurement

Two varieties of apples (Golden Delicious and Rome) were purchased from a local market. The Golden Delicious has a green peel whereas the Rome has a whole red peel. The apples were stored in a dark storage room at 4°C until needed for an experiment. One box of apples at a time was removed from the storage room and each apple was numbered for identification. After the apples were left at room temperature of 23°C, the laser images of apple samples were captured and stored on the computer for subsequent image analysis. The exact spot where the laser beam illuminated was marked and the firmness of the spot was measured by the Magness-Taylor fruit firmness tester.

The fruit firmness tester used in this study was a drill-press mounted penetrometer made by McCormick Fruit Tech., Yakima, Washington (Model FT 3-27#) with a 11.1 mm plunger tip. To measure the MT firmness, a slice of skin at the marked spot was removed with a knife. Then, using the drill bar of the pressure tester, the plunger tip was pressed into the fruit with a steady force until the flesh of the apple ruptured. The firmness reading was measured down to the nearest 0.1 kg_f.

Image Processing and Analysis

The laser images of apple samples were acquired using a monochrome camera or a color camera. While a monochrome image has a single frame for the laser intensity, a color image has three frames for the Red, Green, and Blue color intensity values. When the color camera was used, only the Red frame of color images was used. A laser image was identified with three areas: saturated, scattered and background. The Saturated Area was defined as the area that has the maximum intensity value (255), which can usually be found in the middle of the laser image. The Scattered Area was defined as the area that has the intensity value of below 255 but above or equal to a threshold level. The background was defined as the area whose intensity values are below the threshold level. The Spot Area was also defined as the sum of the Saturated Area and the Scattered Area.

Because of the tripartite nature of the laser images, each acquired laser image was segmented by trinary threshold segmentation. The high threshold value for the trinary segmentation was set to the maximum intensity value of 255 by definition of the Saturated Area. The low threshold value was selected from a histogram analysis to discriminate the laser spot area from the background best.

Eight features of interest were derived from each laser image for further statistical analysis to determine relationships between these feature parameters and the fruit firmness. The eight feature parameters were the area of the Saturated Area (ASAT), the area of the Scattered Area (ASCA), the area of the Spot Area (ASPOT), the ratio of the Saturated Area to the Scattered Area (ARATIO), the total gray level of the Scattered Area (TGSCA), the mean gray level of the Scattered Area (MGSCA), the standard deviation of gray levels in the Scattered Area (STDSCA), and the coefficient of variation of gray levels in the Scattered Area (CVSCA). The area of the Saturated Area was determined by counting the number of pixels with intensity value of 255, and the area of the Scattered Area was calculated by the total pixel number between the low and high threshold values in the histogram. The Spot Area was calculated as the sum of the Saturated Area and the Scattered Area. The total and mean gray levels of the Scattered Area, its standard deviation and coefficient of variation were calculated from the gray level intensity histogram. Statistical analysis was performed by SAS statistical analysis software, release 6.12.

Laser Incident Angle

The laser incident angle was defined as an angle between the laser beam and the optical axis of the camera. If the incident angle is too small, direct reflection of the laser light from the fruit surface can enter the camera and saturate the CCD sensor. Preliminary study also showed that when the incident angle is too large, for example, above 40 degrees, proper laser images could not be captured. In this experiment, laser images of apples with incident angles of 15, 23, and 30 degrees were captured by a color camera to determine the influence of laser incident angles on image features of interest.

Sample Orientation

A term laser plane was defined as the plane that the optical axis of the camera and the incoming direction of the laser beam makes. The sample orientation was defined as the angle between the laser plane and the equator of the fruit, measuring counterclockwise. Thus, at the sample orientation of 0°, the stem end of the fruit pointed upward in the laser image, and the sample orientation angle would increase as the fruit rotates counterclockwise. Four sample orientation of 0°, 90°, 180°, and 270° were tested for their influence on image features of interest.

Laser Optical Power and Laser Wavelength

Four levels of optical power at two different wavelengths of laser beams were compared for their effect on fruit firmness measurement. The optical power output of 632.8 nm He-Ne laser was modulated to 1, 6, 13 and 17 mW using combinations of neutral density filters. The optical power of 685 nm diode laser was also modulated to 3, 6, 12 and 16 mW. Laser images were captures by a monochrome camera.

Results and Discussion

Influence of Laser Incident Angle

Table 2 summarizes effect of laser incident angles on selected laser image features. It confirms that the Saturated Area changed significantly according to the incident angles. This result was expected because as the incident angle increases, the shape of the laser spot area becomes more elliptical and the size of the spot increases as well. The Scattered Area also changed somewhat significantly, but the mean gray level and the standard deviation of the Scattered Area did not have any significant difference according to the incident angles.

No specular reflection or undesirable glare was observed for any incident angle. It was concluded that the incident angle of 15 degrees was adequate to analyze the laser image of apples. Therefore, the laser incident angle was fixed at 15 degrees for remaining experiments.

Influence of Sample Orientation

Table 3 summarizes effect of sample orientation angles on selected laser image features. The statistical analysis showed that no image features were significantly affected by the sample orientation. On the other hand, most features showed significant difference between varieties and between laser wavelengths. It was concluded that the sample orientation was not an important factor to be considered in laser image analysis of fruits. Therefore, the sample orientation of 0° was used for remaining experiments.

Table 2. Significance probability for effect of laser incident angels on selected laser image features

Image Features	Saturated Area	Scattered Area	Mean Gray Level	Standard Deviation
Significance Probability	0.0088**	0.0556	0.6628	0.9301

**highly significant at p=0.01

Table 3. Significance probability for effect of sample orientation angles on selected laser image features

Image Features	Saturated Area	Scattered Area	Mean Gray Level	Standard Deviation
Significance Probability	0.9737	0.7814	0.5562	0.8064

Effects of Laser Optical Power and Laser Wavelength

Unlike the laser incident angle and the sample orientation, optical power levels had highly significant effects on all image features. On the other hand, the laser wavelengths and the apple varieties also had highly significant effects on all image features.

Tables 4 and 5 summarize the best regression models for each wavelength and optical power of the laser beam for Golden Delicious and Rome apples. These equations were used to estimate the firmness of apples from the selected image features in the regression model.

In Table 4, the estimated firmness and the measured firmness had a highly significant correlation with 99% confidence with R-square value of 0.6297

Table 4. Regression models used to estimate the firmness of Golden Delicious apples from image features for each wavelength and optical power of the laser beam

Laser Wavelength	Optical Power	Regression Model	R-square
632.8 nm	1 mW	EF⁺=-17.8+0.00037ASPOT+0.290ARATIO+0.419MGSCA	0.5965**
	6 mW	EF=-8.49-0.00264ASPOT+0.00317ASCA+0.304MGSCA	0.5347**
	13 mW	EF=7.21-0.00126ASPOT-0.130ARATIO+0.000031TGSCA	0.5469**
	17 mW	EF=-0.217+0.00232ASAT-0.475ARATIO+0.646STDSCA	0.5971**
685 nm	3 mW	EF=25.1+0.00293ASPOT-0.0029ASCA-17.8CVSCA	0.6297**
	6mW	EF=-0.174+0.00078ASPOT-0.00334ASAT+0.132MGSCA	0.5967**
	12 mW	EF=6.99+0.00186ASPOT-0.172ARATIO-0.000025TGSCA	0.5265**
	16 mW	EF=1.78+0.000349ASCA+0.286MGSCA-0.180STDSCA	0.4845**

⁺Estimated firmness by regression equation
**highly significant at p=0.01

Table 5. Regression models used to estimate the firmness of Rome apples from image features for each wavelength and optical power of the laser beam

Laser Wavelength	Optical Power	Regression Model	R-square
632.8 nm	1 mW	EF⁺=-2.69+0.000429ASCA+0.471MGSCA-0.334STDSCA	0.3657**
	6 mW	EF=6.00+0.00168ASAT-0.523MGSCA+0.560STDSCA	0.5640**
	13 mW	EF=-6.93+0.000088ASCA+0.403MGSCA-0.174STDSCA	0.3936**
	17 mW	EF=13.3+0.00126ASAT-0.395MGSCA+0.312STDSCA	0.3546**
685 nm	3 mW	EF=7.16+0.000407ASCA+0.0473MGSCA-0.0984STDSCA	0.2478
	6 mW	EF=-11.2-0.00351ASAT+18.3CVSCA+0.000013TGSCA	0.2833*
	12 mW	EF=-36.1+0.000431ASPOT+0.265ARATIO+41.7CVSCA	0.3238*
	16 mW	EF=11.5+0.00200ASPOT-7.48CVSCA-0.000028TGSCA	0.2484

⁺Estimated firmness by regression equation.
*significant at p=0.05.
**highly significant at p=0.01.

when illuminated by 685 nm diode laser with 3 mW optical output. For this model, the estimated firmness slightly overestimated the actual firmness at the lower firmness range, and slightly underestimated at the higher firmness range. Mean difference between the measured and the estimated firmness was 0.68 kg_f with 0.37 kg_f standard deviation.

In Table 5, The estimated and measured firmness of Rome apples also had a highly significant correlation with 99% confidence with R-square value of 0.5640 when illuminated by 632.8 nm He-Ne laser with 6 mW optical output. Mean difference between the measured and the estimated firmness was 0.51 kg_f with 0.50 kg_f standard deviation. The firmness of Rome apples was generally lower than that of Golden Delicious apples.

Conclusion

A laser vision system was set up to evaluate quality parameters of fruits nondestructively. A He-Ne laser at 632.8 nm wavelength and a diode laser modules at 685 nm wavelength were used as a light source. Combinations of neutral density filters were used to modulate the optical output of the laser light source. Eight features of interest were derived from laser images to estimate the fruit firmness using multiple regression analysis. The estimated and measured firmness were compared statistically to evaluate effects of different laser wavelengths, output power levels, incident angles and sample orientation on fruit firmness measurement. A series of experiments was conducted using two varieties of apples (Golden Delicious and Rome), and the following conclusions were made:

1) The laser incident angle of 15 degrees was recommended for capturing laser images of apples without a specular reflection or undesirable glare.

2) Sample orientation to the optical axis of camera and the direction of the laser beam did not affect the image features of interest.

3) Optical power levels and wavelengths of laser beams affected the system performance in estimating apple firmness within the range of power levels tested.

4) Laser image analysis was able to estimate apple firmness from derived laser image features. Correlation between the estimated and measured firmness was highly significant with mean difference of less than 0.68 kg_f for Golden Delicious and Rome apples

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