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BARD

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FINAL REPORT

PROJECT NO. US-1573-88

Photometric Imaging for Detecting Surface and Internal Defects on Apples

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DATE: February 11, 1993

BARD
P.O. Box 6
Bet Dagan, ISRAEL

BARD Project No. US-1573-88R

Title

Photometric Imaging for Detecting Surface and Internal Defects of Apples

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Project's Starting Date: October 1, 1989

Type of Report: 1st Annual   2nd Annual   Final   X

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The focus of this research project was to develop a photometric imaging system for detecting bruises on Red Delicious and Golden Delicious apples. As part of the project, an investigation to characterize the physical and chemical alterations that occur when an apple is damaged was undertaken. Project objectives were 1) to characterize the anatomical and chemical changes for bruising, shape, russetting, and external insect damage and how these changes vary with time on Red Delicious, Golden Delicious, and Empire apples, 2) to define the chemical changes for the previously specified apple varieties, and 3) to evaluate the selected photometric sensor and image processing techniques for determining the feasibility of distinguishing good tissue from each defect and each defect type from each other.

Apple tissue undergoes both chemical and anatomical alterations when cells are damaged. Studies indicated that CO₂ production increased while ethylene production decreased for bruised tissue regions. Membrane permeability increased for bruised tissue and was proportional to the severity of the bruised region. This change in the permeability resulted in an increase in the electrical conductance for bruised apple tissue.

There are limitations of applying spectrophotometric results into a machine vision inspection system. Although specific wavelengths for increasing the contrast between bruised and nonbruised were identified, the contrast between bruised and nonbruised regions actually decreased when the specific wavelengths were implemented in a machine vision system. Bruise detection using near-infrared reflectance varied with time. For a 24 hour bruise, the energy reflected from a bruised region was less than the energy reflected from a nonbruised region. However, the energy reflected from a bruised region exceeded that from a nonbruised site for older bruises. Red, green, and hue were selected as the best features for discriminating bruises on stored Golden Delicious apples. These three features did not exhibit an increase in reflectance for older bruises that was evident with near-infrared reflectance.

Three algorithms for tracing the boundary of pixel clusters were evaluated for their accuracy from measuring the area and efficiency in computation. The CLUSTER and BOUNDARY algorithms were not significantly different in performance or speed, while CENTROID was slowest.

INTRODUCTION

Commercial apple production has increased over the past 25 years despite a decline in the number of acres in production. This continued increase will force the grower to adopt new production practices, because the labor force for harvesting and handling the fruit is declining. Unless the grower can harvest and process the fruit before its quality deteriorates, the fruit will be worthless.

Fruit quality depends on several characteristics that indicate the acceptability of the product to the consumer. For apples, grade is determined by maturity, shape, disease, damage, and color. The complex procedure by which apples are graded is described in the standards adopted by federal government agencies. A satisfactory method for automatically segregating blemished apples is lacking and has led to a labor intensive process for apple inspection. The failure of fully automating apple inspection has led to the following effects on the apple industry in both the United States and Israel:

1. Twenty-five years of mechanized harvesting research has not proved feasible for fresh market apples because of the need for a rapid automated sorting system to remove damaged fruit (Millier et al., 1983, 1984; Tene et al., 1973; Peterson, et al., 1985).
2. Although present technology has automated color and weight sorting, removal of damaged and diseased fruit still remains a labor intensive process.
3. Human failure and fatigue during inspection causes error in equity of payments to producers and variable market quality for the consumer (Rehkugler, 1986). Studies have shown variability in the implementation of the grading standards between packing houses and within a packing house (Stevens and Gale, 1970).
4. Complete sorting of stored apples to eliminate storing damaged fruit that decays and causes spoilage of neighboring good fruit is not fully implemented because the amount of labor necessary to inspect the volume of fruit during the short harvest season cannot be economically justified. However, high speed automatic sorting could make this procedure feasible.

There have been numerous attempts to identify features that could be used to distinguish blemished from unblemished fruit. Many parameters have been identified; however, none have been successfully incorporated into a grading system. Implementation of a successful automatic grading mechanism requires a device that can sense and differentiate many types of fruit characteristics at a high rate of speed and accuracy.

OBJECTIVES

The original objective of this research project was to define a photometric measurement technique for detecting different defects on apples and investigate how these techniques could be applied in a prototype grading system. The specific objectives were:

1. Characterize the anatomical and chemical changes for bruising, shape, russetting, and external insect damage and how these changes vary with time on Red Delicious, Empire, and Golden Delicious apples.
2. Define the relationship between the photometric measurement and the anatomical and chemical changes for the previously specified apple varieties.
3. Evaluate the selected photometric sensor and image processing techniques for determining the feasibility of distinguishing good tissue from each defect type and each defect type from each other.

During the course of the project, the objectives were modified. The type of defects and the cultivars of apples were reduced. Characterization of bruise damage was investigated only on Red Delicious and Golden Delicious apples. This limitation focused the research on the main fresh market cultivars. Quality factors such as shape, russetting, and insect damage were omitted; however, time and storage effects on the dissipation of watercore and development of internal browning were investigated. This change was made, because earlier time studies indicated that the light transmission properties of watercored fruit changed with time and storage conditions. Lacking the input from a postharvest physiologist at the Appalachian Fruit Research Station, no progress was made on evaluating the relationship between the photometric measurement and the anatomical and chemical changes of the various defects.

RESEARCH ACTIVITIES AND RESULTS

Physiological Changes for Alternative Detection

Bruising of apples occurs by compression and impact damage during handling, packaging and transport operations. The result is a loss of prime quality and reduced grades of the fruit on the market. There is an increasing demand to grade fruits for quality and appearance and at present, most of the inspection is done manually. An objective, mechanized technique for produce inspection is needed by the fruit and vegetable sorting, grading and packing industries. Various automatic techniques that have been investigated are based on detection by computer vision using near-infrared (Taylor and Rehugler, 1985), x-rays (Johnson, 1985), NMR (Chen et al., 1988) and even computer tomography for internal quality (Moroshima et al., 1987). All these methods are aimed at visualizing the defective tissue and thereafter interpreting and translating the vision to a data processing system, which, of necessity has to be very rapid. One of the difficulties with these methods for computer imaging of bruised tissue is, that a bruise generally becomes visible to the naked eye and to the apparatus, some time after the damage has occurred. However, prior to the change in color, a number of physiological and biochemical alterations occur, leading among other things, to the change in color. The object of this study was to characterize some of these changes, with the idea that they might be used as attributes to identify damaged tissue, even at an early stage after its induction.

Selected damage-free fruits of uniform size from two cultivars, Golden Delicious and Starking Delicious were harvested at three stages of maturity. Fruit samples were subjected to measured degrees of impact force, either after

harvest or after various storage periods. The different degrees of impact force were achieved by dropping a 4 cm diameter metal disc, weighing 364 g, from different heights onto the exposed cheek of each fruit. The impact of the disc on the fruit caused a regular circular bruise, the size of which was proportional to the impact force. Physiological responses were monitored at predetermined times immediately following treatment or after cold storage in air or controlled atmosphere (CA: 5% CO₂, 2% O₂). The parameters measured were:

- a) Changes in color measured by reflectance from bruised tissue, using a Minolta chromameter CR-200.
- b) Respiration and ethylene evolution by whole fruits and from excised bruised tissue compared to excised healthy tissue from the same fruits.
- c) Electrolyte leakage from bruised tissue as a measure of membrane damage.
- d) Conductivity of bruised tissue compared to healthy areas of the same fruits.
- e) Acidity of bruised versus healthy tissue, by titration of extracted juice.
- f) Changes in the activity of the ethylene forming enzyme (EFE) in vivo.

a) Bruise detection by tristimulus color measurement

Differential color estimations of bruised vs. healthy tissue (ΔE^*_{ab}), based on Commission International de l'Eclairage (CIE, 1986) L* a* b* (CIELAB) values, correlated well ($R^2 = 0.57$) for green Golden Delicious apples when the total color difference (ΔE^*_{ab}) was calculated as follows:

$$\Delta E^*_{ab} = (\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2$$

As fruit matured, the quantitative color differences diminished, even though the bruises remained visible. A similar situation was observed on bruised fruit that was examined after storage. The above correlation did not hold true for bruises on the red cheeks of Starking Delicious apples.

b) Respiration and ethylene evolution

The respiratory activity and ethylene evolution by whole fruits immediately after impact bruising were essentially the same as reported previously by other investigators (Robitaille and Janick, 1973; Klein, 1983), for both freshly harvested fruits and for post-storage treated fruits (Table 1).

The enhancement of CO₂ production was generally less pronounced with the 2 cvs. studied here, but the inhibition of ethylene evolution was much the same. However, neither respiration rate nor ethylene evolution from stored-bruised fruit showed any consistent significant deviation from those of undamaged fruit, after the removal of the fruit from air or CA storage.

Comparisons drawn between the CO₂ production rates of excised bruised and healthy tissues from the same fruits showed no effect on bruising at any time. Moreover, no differences could be found in the titratable acid content of bruised and healthy tissue. The enhanced malate decarboxylation effect of bruising, proposed by Klein (1983) to explain the increased CO₂ production

Table 1. CO₂ and C₂H₄ production by discs of bruised apple tissue (expressed as % of production by non-bruised tissue discs) excised from fruits at different stages of the climacteric after impact bruising from different heights.

Cultivar	Location	Harvest Date	Impact Ht. (cm)	CO ₂ a			C ₂ H ₄ a		
				Pre	C1	Post	Pre	C1	Post
Golden Delicious:	Valley	28/8/90	10	114	-	71	-	61	37*
			15	115	119	-	-	48*	-
			20	122	113	86	-	40*	28*
		11/9/90	10	111	121	71	52	52*	32*
			15	128	92	-	77	35*	-
			20	106	104	79	30*	32*	37*
		18/9/90	10	-	89	93	-	65*	35*
			20	-	111	95	-	38*	33*
		2/20/90	10	-	125	89	-	69*	77
Starking Delicious:	Plateau		20	-	97	95	-	59*	62

a - Production 4h after impact
 Pre - preclimacteric fruit
 C1 - at climacteric peak
 Post - postclimacteric fruit
 * Differs from control at p=0.05

from damaged fruits, does not appear to apply for Golden Delicious apples. This might be due to the low level of acidity in Golden Delicious as compared to McIntosh. It would therefore seem that increased CO₂ production does not necessarily accompany bruising of apples.

On the other hand, when comparisons were drawn with regard to ethylene evolution, consistent inhibition was observed for at least 6 hours after impact. The extent of inhibition was relative to the severity of the bruise at 2 hours after impact, but the differences diminished somewhat thereafter. At 24 hours after excision, when wound ethylene was no longer being produced, only the more severely bruised tissue produced ethylene at a lower rate than that of the healthy tissue. Even though the ethylene produced by intact stored-bruised fruit did not appear to have been affected by prestorage bruising, production by excised bruised tissue was reduced relative to that of excised healthy tissue from the same fruits (i.e. with respect to ethylene evolution, stored-bruised tissue behaved in a similar manner to freshly bruised tissue). Measurement of EFE activity indicated that a decline in the ability of this enzyme to catalyze the formation of ethylene from aminocyclopropane-1-carboxylic acid (ACC), is likely to be the cause of reduced ethylene production in bruised tissue.

c) Membrane permeability

Membrane permeability changed with fruit maturation; however, bruising increased the amount of electrolytes leaking out of the tissue plugs. The maximum response to bruising took longer to develop than either change in color or reduction in ethylene evolution, and was achieved at about 90 minutes after bruising. The effect of bruising on membrane permeability was not reversible and could be measured to a similar extent in bruised-stored fruits and under all conditions of impact. The extent of leakage was in proportion to the severity of the bruise and to the force of impact. Leakage from lightly bruised tissue, achieved with the lowest impact force used, was not always significantly higher than that from the healthy tissue of the same fruits.

d) Tissue conductivity

The consistent effect of bruising on electrolyte leakage from damaged tissues compared to healthy tissue from the same fruits, led us to try to measure this difference in intact fruits. The use of a conductivity bridge and 2 syringe needles to serve as electrodes, enabled us to monitor significant differences in the conductivity of bruised and healthy tissues. The conductivity of the bruised tissue increased rapidly relative to that of the surrounding healthy tissue, within 30 minutes after impact, and in proportion to the force of impact ($R=0.84$). This was true for all fruit examined within 24 hours after bruising and the difference tended to increase as the fruit ripened and senesced (i.e. became more susceptible) (Klein, 1987).

Since the above method requires penetration of the fruit surface, attempts were made to develop a nondestructive technique for detecting the changes in internal conductivity by monitoring differences in conductivity around the fruit surface. Unfortunately, the use of primitive equipment prevented the collection of conclusive data. It is still possible that with more sophisticated equipment meaningful data could be obtained.

Of the four physiological parameters found to change in bruised apple tissue, electrical conductivity appeared to be the most reliably consistent and highly correlated with bruise severity. Moreover, it was rapidly detectable and long lasting. The difficulty remains of finding a suitable method for detecting the signal nondestructively. In all events, detection of real differences will require direct contact between a suitable probe and the entire fruit surface. Therefore, it might not be a very practical solution without an ingenious idea of how it can be implemented.

Spectrophotometric Characteristics of Bruised Tissue

Numerous attempts have been made to identify the destructive and nondestructive methods that could be used to distinguish between bruised and nonbruised surface tissue on apples. Brown et al. (1974) and Reid (1976) demonstrated that freshly bruised tissue has a lower reflectance than nonbruised tissue in the visible through near-infrared. Bilanski et al. (1984) and Pen et al. (1985) reported specific wavelengths for distinguishing between the bruised and nonbruised tissue on peeled apples. The wavelengths of their studies ranged from 350 nm to 750 nm. Upchurch et al. (1990) investigated the diffuse reflectance in the 400 to 1000 nm wavelength region

for bruised and nonbruised areas on whole Red Delicious apples. From the reflectance spectra data, different models were developed, and wavelengths most related to bruised areas were identified for each model by linear regression analysis. Only 2.5 - 3.5% of the fruit misclassified resulted from this study.

This project was devoted to study the spectrophotometric characteristics of bruised surface tissue on Golden Delicious apples, in the range of 400 to 840 nm, as a first step toward the development of a nondestructive method for detection of fresh surface bruises caused by impact. The specific objective was to define a classifier that uses the diffuse light reflectivity characteristics at one or more pre-defined narrowbands in the spectrum.

Apples were harvested from different growing regions in Israel and stored at 0° C in air. The apples used for each set of experiments were from the same harvest. Experiments were conducted with apples from air storage (stored apples) at different times of the year, so that the used apples were from 1 to 6 months old. A series of experiments were also conducted with fresh (nonstored) apples during the harvesting seasons. Prior to each experiment, a certain number of apples were removed randomly from storage and allowed to equilibrate at room temperature for 1 hour. The apples for the experiment were randomly selected and bruised by a device identical to the one designed and used by Upchurch et al. (1990). The device consisted of a transparent open ended PVC tube of 4 cm diameter and 35.6 cm height containing a plunger with a 3.9 cm diameter steel disk, weighing 364 g.

Diffuse reflectance of surface tissue of bruised and nonbruised apples was measured using a Philips PU-8000 double beam scanning computerized spectrophotometer equipped with an integrating sphere. The wavelength resolution was 2 nm. The spectrophotometer was calibrated using a standard white sample of known spectrum for 100% reflectance. In the initial stage, reflectivity values of the surface tissue in the range of 400 to 840 nm were obtained for 100 nonbruised stored apples, 100 stored apples that were bruised and maintained at room temperature for 24 hours, and 100 stored apples that were bruised and maintained at room temperature for 90 minutes. In all of the reflectivity measurements, the cheek of interest was sliced appropriately since the sample compartment of the spectrophotometer could not contain a whole apple. The sliced pieces with a minimum thickness of 15 mm, at the target area, were then easily placed against the objective aperture of the integrating sphere. It has to be mentioned that maintaining bruised apples at room temperature allowed for bruise development, thus affecting the reflection of surface tissue. The error of classification of the selected model and selected waveband were tested on a prediction set consisting of 200 stored apples (100 bruised and 100 nonbruised) and 200 fresh nonstored apples (100 bruised and 100 nonbruised).

For each set of experiments an average reflectivity spectra was obtained. The maximum, minimum, and average reflectance spectra of nonbruised and bruised surface tissue after 90 minutes and 24 hours are shown in Figures 1 and 2, respectively. Comparing the spectra in Figure 1, bruised apples which were maintained for 90 minutes after impact reflected less of the radiation between 400 and 800 nm than nonbruised apples. The amount of reflected energy from tissue of bruised apples which were maintained for 24 hours after impact (Fig. 2), was less between 400 and 600 nm when compared to nonbruised apples.

Figure 1. Average, minimum, and maximum reflectance spectra from the surface of Golden Delicious apples after 24 hours.

Figure 2. Average, minimum, and maximum reflectance spectra from the surface of Golden Delicious apples after 90 minutes.

However, reflected energy in the 600 to 700 nm region from bruised apples exceeded the corresponding values of the nonbruised apples. From wavelengths 700 nm up to 840 nm, the reflectivity values of the nonbruised surface tissue exceeded the corresponding values of the bruised surface tissues.

The next step toward accomplishing the main objective of the project was to develop a classification criteria by which the bruised and nonbruised surface tissues could be distinguished. In the present study a relation of the following type was considered:

$$M = f(r_{\lambda i}) \quad (1)$$

In equation (1), $r_{\lambda i}$ represented the reflectance value at a wavelength λ_i , where i indicates the discrete wavelength involved in computation of the value of M (note that i does not represent a sequential order). Most of the models tested in this study were presented earlier by Upchurch et al. (1990). The models were:

$$M = r_{\lambda 1}$$

$$M = (\sum_{i=1}^n r_{\lambda i})/n$$

$$M = r_{\lambda 1}/r_{\lambda 2}$$

$$M = r_{\lambda 1} - r_{\lambda 2}$$

$$M = (r_{\lambda 1} - r_{\lambda 2})/r_{\lambda 3} \text{ or } r_{\lambda 1}/(r_{\lambda 2} - r_{\lambda 3})$$

$$M = (r_{\lambda 1} - r_{\lambda 2})/r_{\lambda 3} - r_{\lambda 4}$$

$$M = (r_{\lambda 1} - r_{\lambda 2})/(\lambda_1 - \lambda_2)$$

In equation (8), M represents the slope of the connecting line between two selected points. In addition to the above equations, a few biased models with different weighting factors were tried which were unsuccessful. The above models were studied and tested on the basis of the reflectance spectra data of nonbruised tissue. In other words, the developed model predicted a nonbruised tissue. Each model after its development (i.e. once the values of λ_i were determined) was applied to the data of bruised apples, to check the validity of the model for bruise detection.

In general the models involving subtraction of reflectivity values, (i.e. models 5 through 8 are reasonable choices when the differences are large enough to cover the unpredicted measurement errors. Each of the above models was studied and tested in selected narrow wavebands in the range of 400 to 840 nm; however, wavelengths between 400 to 720 nm were not selected for reliable bruise detection purposes.

Formal comparison of models (2) and (3) indicated that model (2) was much simpler to use since it involved the magnitude of reflectance at a single wavelength. However, due to unexpected sources of errors, fluctuation in the magnitude of the reflection data, and identifying a single reflectance wavelength, models based on a single term were subject to large classification errors. Therefore, model (3) was selected as the mathematical model of bruise detection. Further experiments with the existing data also revealed that wavelengths of interest could be reduced from 720 - 840 nm and 750 - 800 nm when using the ratio as the model of bruise detection. The average reflectance in the waveband 750 to 800 nm for the nonbruised apples was found to be 80.74% with a standard deviation of 0.93. For 95% confidence limit the lower band reflection for acceptance of nonbruised apple was found to be 78.88%. On the basis of the present data at this stage, it was concluded that an apple could be classified as nonbruised if $\bar{r} \geq 78.88\%$ and classified as bruised if $\bar{r} < 78.88\%$ where $\bar{r}$ represents the average reflectance of surface tissue of a Golden Delicious apples in the range 750 to 800 nm. To examine the validity of the selected waveband and classifying model, 300 stored apples of which 100 were nonbruised, 100 bruised and kept for 90 minutes at room temperature and 100 bruised and set for 24 hours at room temperature were examined. The result of classification of the experiment is shown in Tables 2 and 3.

Table 2. Results for the ratio model when applied to 300 apples from storage

Percent (%) Correctly Classified	
<u>Nonbruised</u>	<u>Bruised</u>
96.1	88.4 (after 90 min.) 98.7 (after 24 hours)

Table 3. Results of the ratio model when used to classify bruised tissue on nonstored apples.

Percent (%) Correctly Classified	
<u>Nonbruised</u>	<u>Bruised</u>
92.9	91.8

Development of a relatively quick spectrophotometric method of bruise detection of Golden Delicious apples was the main objective of this study. Average reflectance in the wavelength ranging from 750 to 800 nm produced the best criteria for classification of Golden Delicious apples for bruise detection. Application of the method showed misclassification errors of 3.9%, 11.6% and 6.0% for nonbruised, bruised (90 minutes) and bruised (24 hours) stored apples, respectively. This method was also applied to fresh nonstored apples which resulted in misclassification errors of 7.1% with nonbruised and 8.2% with bruised apples.

Spectrophotometric Results and Machine Vision.

Past research on automatic bruise detection on apples has emphasized differences in the near-infrared reflectance between bruised and nonbruised tissues. Utilizing advances in computer vision technology in conjunction with near-infrared reflectance, identification of bruised regions on apples has been attempted with matrix as well as line scan cameras (Graf et al., 1981; Taylor et al., 1984; Rehkugler and Throop, 1986, 1987; Davenel et al., 1988). Earlier spectrophotometric studies had shown that bruised apple tissue had a lower reflectance in the visible through near-infrared region (Brown et al., 1974). Later studies had identified specific wavelengths in the near-infrared region that could be used to enhance the difference between bruised and nonbruised regions on nonpeeled apples (Upchurch et al., 1990). In the study by Upchurch et al. (1990), the ratio between the reflectance at 780 and 830 nm resulted in a misclassification error of less than 5% on nonpeeled Red Delicious apples. However, there has been no attempt to implement and test these wavelengths in a machine vision system. The objective of this project was to evaluate the effectiveness of narrow band filters in a machine vision system for enhancing the contrast between the bruised and nonbruised regions on Red Delicious apples.

A sample of 85 Red Delicious apples were hand harvested and stored in conventional cold storage (0° C). Each apple was bruised by dropping a 39 mm

steel disk a distance of 200 mm onto the surface of the fruit. Prior to capturing an image, the apples were held at room temperature for 24 hours to allow for bruise development. Apples were individually rotated before a line scan camera in a diffusely illuminated chamber (Taylor, 1985). Images were captured at each wavelength band. Filters used in front of the camera were a 780 nm with a 11 nm bandwidth, 830 nm with a 12 nm bandwidth, and a long pass near-infrared filter. An image size of 64 pixels (row) by 240 pixels was acquired. Algorithms were written to align the images so that a final image could be generated by a pixel-pixel division between the 780 and 830 images. A mean gray-level within a 15 by 15 pixel window was used as a measure of the reflectance from bruised and nonbruised regions on individual apples.

The contrast improvements for the four different filtered images are shown in Figure 3. Each profile is a plot of the gray-levels for a single row of pixels that bisected a bruised region on an apple. From this sequence, the reflectance difference between bruised and nonbruised regions was greatest in the 780 and long pass near-infrared images. Ratioing the 780 and 830 images actually reduced the difference between bruised and nonbruised regions without reducing the pixel-to-pixel variations in the image. A comparison of the mean gray-level for the two regions exhibited similar results (Table 4). The

Figure 3. Gray level profile of a single row of Pixels that bisected the bruised region at a) 789 nm, b) 830 nm, c) ratio 780/830, and d) NIR Long Pass.

broadband near-infrared image yielded the best contrast between bruised and nonbruised regions. Assuming a normal distribution of the means, the broadband misclassified 18.7% of the nonbruised regions and 14.4% of the bruised ones. The errors occurring with the 780 image were comparable to the broadband images. However, there was a significant difference in errors in both the 830 and ratio images. Both sets of images had errors in excess of 25%.

Table 4. Probability of incorrectly classifying bruised and nonbruised regions in an apple image.

Image Type	Misclassification (%)	
	Bruised as Nonbruised	Nonbruised as Bruised
780	20.9	19.1
830	34.9	26.3
NIR	18.7	14.4
Ratio	33.4	33.8

Although Upchurch et al. (1990) showed that the ratio improved bruise detectability, contradicting results were found when the fiber optic detector was replaced with a camera and lense system. The bruise was evident in the 830 nm image while 830 nm in the spectrophotometric study was not highly correlated with bruised regions.

Several possible factors could contribute to the lack of success in implementing the spectral information into a machine vision system. First, a difference in precision existed between the two instrumentation systems. The spectrophotometer had the capability to measure smaller changes in reflectance compared to the machine vision system. Another factor is nonlinearity response of the solid-state camera. Finally, the bruise cannot be considered a surface defect, but is a subsurface one that is covered by an infinite thick (compared to the wavelength) layer. The peel is a diffusely reflecting layer that masks part of the energy being reflected from the bruised tissue. In the spectrophotometer, the light source and detector were arranged so that the light energy from the apple tissue was the main reflection.

Time Effects on Detecting Bruises.

Detecting differences in the near-infrared reflectance between bruised and nonbruised regions on apples has had limited success with machine vision systems. As shown by previous research, automatic bruise detection is a difficult problem caused by the wide variability in reflectance between apples and within a single fruit. Temporal factors have not been formally analyzed. As the bruise ages, the near-infrared reflectance from that region also changes (Brown et al., 1974; Graf et al., 1981). The objective of this experiment was to evaluate time effects on the near-infrared reflectance from bruised and nonbruised regions on apples.

Red Delicious and Golden Delicious apples were hand harvested in mid-September during the 1991 season. A total of 64 fruit for each variety were placed in tray packs and stored in conventional cold storage at 0°C. Prior to the first

inspection date, each fruit was bruised by dropping a 39 mm diameter steel disk from a distance of 200 mm onto the surface of the fruit. Samples were held at room temperature, 20°C, for 24 hours to allow for the damaged area to develop the browning that is indicative of bruise damage. For each sampling date, fruit were removed from storage 24 hours prior to inspection. Images of each apple were acquired at one month intervals for two months beginning in November.

Images of apples were acquired by digitizing the output from a RS-170 solid-state camera. A PC-based system equipped with a Data Translation frame grabber and frame processor was used to acquire the images. Images were transferred to a VAX 4000/200 (Digital Equipment Corp.) and analyzed with image processing software from Euclid Computer Co. A CCD array camera (Model 4810, COHU Electronics) without the infrared blocking filter was used to acquire images of the apples. A 25mm lense with an aperature set at f1.4 was mounted to the camera. To limit the reflectance from the apple to the near-infrared region, a long pass filter (Kodak Wratten 89B) was placed between the camera lense and apple. Two images of each apple were captured. The bruised region was centered in the initial image while a second image was acquired after rotating the apple 135° so that the bruised region was absent in the image. To maintain equivalent measurements between dates, a reference image of a teflon cylinder was acquired at four times on each date.

The mean value of the pixels around a circular profile at 1° increments was a measure of the intensity of near-infrared reflectance (NIR) from bruised and nonbruised regions. Three concentric circles were used (Figure 4).

Figure 4. Diagram showing the location of the 3 concentric profiles on the apple.

Initially, the center of the bruised region was interactively identified in the image and used as the center for the concentric profiles. To determine the diameter of the outer two circles, the outer edge of the bruised region in the y-direction was measured interactively. The diameter of the middle profile was twice the difference between the center and outer location minus 30 pixels while the outer circle had a diameter twice the difference plus 30 pixels. The third circular profile had a constant diameter of 10. After measuring the mean gray value around each circle, the three profiles were applied to the nonbruised side. Each mean value was divided by the mean for the reference and then multiplied by 255. Since the relative changes in reflectance between bruised and nonbruised regions were important, the

difference between adjacent profiles (nonbruised - bruised) were calculated and compared. This procedure was repeated on the nonblemished side by calculating differences between nonbruised regions.

Time had a significant effect of the near-infrared reflectance from bruised and nonbruised regions on both Red Delicious and Golden Delicious apples. Comparing a linear profile that dissected a bruised region, the reflectance from a bruised region decreased to minimum level with time (Figure 5).

Figure 5. Linear profiles showing the pixel intensities across the apple and how the reflection from a bruised region changes with time.

The maximum difference in reflectance usually occurred 24 hours after inducing the bruise. After one month in storage, the reflectance from the bruised regions increased to a level equivalent to the reflectance from nonbruised regions. This increase in reflectance continued until the reflectance from bruised regions exceeded that from nonbruised regions. Reflectances from Golden Delicious exhibited similar changes with time. The two profiles from the bruised regions on Red Delicious and Golden Delicious apples were significantly different ($P < 0.05$) from the nonbruised regions for the 24 hour test (Tables 5 and 6).

Table 5. Effects of time on the reflectance from bruised and nonbruised regions on Red Delicious apples as measured by the mean gray-level of a circular profile.

Profile Size	TEST DATE					
	Nov		Dec		Jan	
	Mean	Std	Mean	Std	Mean	Std
BRUISED SIDE						
small	231 ^a	8.0	235 ^a	6.5	244 ^a	4.1
medium	230 ^a	8.4	235 ^a	7.3	247 ^b	3.8
large	241 ^b	7.6	238 ^a	5.0	242 ^a	3.7
NONBRUISED SIDE						
small	244 ^b	7.5	242 ^a	5.0	244 ^a	4.9
medium	243 ^b	7.5	241 ^a	5.1	244 ^a	4.5
large	242 ^b	7.5	239 ^a	4.8	243 ^a	4.4

^a Means with the same letter are not significantly different at 95% confidence level.

Table 6. Effects of time on the reflectance from bruised and nonbruised regions on 'Golden Delicious' apples as measured by the mean gray-level of a circular profile.

Profile Size	Nov		Dec		Jan	
	Mean	Std	Mean	Std	Mean	Std
BRUISED SIDE						
small	238 ^c	5.5	244 ^b	3.1	244 ^a	7.4
medium	237 ^c	4.8	246 ^a	2.8	244 ^a	7.2
large	246 ^b	4.4	236 ^a	3.1	244 ^a	7.4
NONBRUISED SIDE						
small	247 ^a	5.0	244 ^b	3.3	243 ^a	7.6
medium	246 ^b	4.6	244 ^b	3.1	242 ^a	7.5
large	249 ^b	5.4	245 ^a	3.4	243 ^a	7.8

*Means with the same letter are not significantly different at the 95% confidence level.

For both varieties, there were no significant differences between the four nonbruised profiles. After one month in storage, the mean reflectance from bruised regions increased to a level where there were no significant differences between any profiles. A significant difference only existed for the middle profile from the bruised region for the third test date on Red Delicious (Table 5). However, there were no significant differences between the profiles on Golden Delicious for the final date (Table 6).

Automatic bruise detection by machine vision depends upon the ability of the system to detect spatial and magnitude relationships between groups of pixels. The maximum difference in reflectance between bruised and nonbruised areas was 16 gray levels which is approximately a 10-15% decrease in reflectance (Figure 6).

Figure 6. Distribution of the differences between the larger two profiles on the bruised side of the fruit. A negative difference indicated that the reflectance from the bruised region was greater than that from the adjacent nonbruised site.

This maximum difference occurred between the larger two profiles on the bruised side. For the 64 Red Delicious apples, the mean difference was initially 11.3. This mean difference decreased to 3.5 in December and -4.5 in January. A negative difference indicated that the reflectance from the bruised region was greater than the adjacent nonbruised site. Mean differences among the nonbruised regions were within 2 gray levels for the three test dates.

Near-Infrared reflectance from bruised regions on Red Delicious and Golden Delicious apples changed with time while the reflectance from nonbruised regions remained relatively constant. This change in reflectance is critical when machine vision systems are being designed to automatically detect bruises on apples. An automatic bruise detection system must be able to detect bruises of various ages. However, the detection is more difficult when the amount of light reflected from the bruised area varies with time.

Color Image Processing of Golden Delicious Apples.

The appearance of Golden Delicious apples is the primary factor on which the consumer makes a purchasing decision. The consumer expects bruise and blemish free fruit. The eye is a sensitive sensor that uses spectral reflectance from the apple surface to judge overall quality. As the technology became available, it was only natural for scientists to measure surface reflectance to quantify apple quality and maturity.

Mechanical injury of Golden Delicious apples can result in softening and discoloration of the tissue under the apple's skin. The discoloration or browning of fruits is ascribed to the oxidation and polymerization of phenolic compounds (Walker, 1964). Unlike red cultivars which tend to mask the browning, the partially translucent yellow skin of Golden Delicious apples allows the browning to show through the skin in sharp contrast to the uniform fruit color. Spectral reflectance at 600nm was used to measure browning on Golden Delicious apples and was correlated with time and temperature (Ingle and Hyde, 1968). Discoloration was expressed as the difference between normal and injured tissue reflectance. Golden Delicious were found to discolor erratically and more slowly than other cultivars and temperature was found to have little effect on the rate of browning (Ingle and Hyde, 1968). The reduction in surface reflectance between normal and bruised tissue for Golden Delicious was found to be about 8% compared to 11% for red cultivars such as Red Delicious and McIntosh (Ingle and Hyde, 1968). Surface reflectance using wavelengths between 700 - 2200nm was reduced for bruised compared to normal Golden Delicious tissue (Brown et al., 1974). The significance of this finding was that it removed color variations from the reflectance measurement for bruised tissue. All of the above surface reflectance measurements were made with spectrophotometers and would not be applicable to high speed measurement required on packing lines.

Digital image processing can measure surface reflectance over the total fruit surface to find areas of lower surface reflectance which could be bruises. This method has the potential to measure surface reflectance of a stream of apples on the packing line. Linear discriminate classifiers were determined from a training set of apples with known bruise areas (Graf, 1982). Predicting bruised tissue on Golden Delicious apples, NIR reflectance for wavelengths between 750nm to 850nm showed correlations to actual bruising of 0.22 compared

to 0.72 or better for Delicious and McIntosh (Graf, 1982). When the apples were cut after testing, a layer of good tissue cells was found just under the skin of the Golden Delicious, unlike Delicious and McIntosh which had damaged cells (Graf, 1982). This observed reduction in surface reflectance in both the visible and NIR wavelengths for bruised tissue on Golden Delicious apples leads to the objectives of this study to examine digital imaging of diffuse surface reflectance in the visible and NIR spectrums as methods for detecting bruises on Golden Delicious apples and determine which features of reflected light (NIR, RGB, and HSI) are the most effective for detecting damaged tissue on Golden Delicious apples before and after storage.

A group of 88 Golden Delicious apples were hand harvested in mid-September during the 1991 harvest season at the Appalachian Fruit Research Station in Kearneysville, WV. A 39 mm diameter steel disk was dropped onto the surface of each fruit. Samples were held for 24 hours at 20°C to allow full bruise development and then digital images were captured (time 1). Thereafter, images were grabbed twice at one month intervals (time 2 and time 3). The apples were removed from cold storage 24 hours prior to imaging and held at 20°C. Two 512 pixel x 512 pixel images (NIR and RGB) of every apple were acquired; one with the bruise normal to the lense and a second with the bruise rotated 105 degrees away from the lense axis displaying only undamaged tissue. Image processing of all images consisted of interactively locating and recording the location of the center of the bruised area as described in previous section.

Surface reflectance of nonbruised tissue for Golden Delicious was found to decrease significantly from the fruit center outwards for the reflectance features of NIR, red, green, blue, hue, and intensity ($p < 0.01$). However, saturation exhibited a significant ($p < 0.01$) increase. A color difference for good tissue was found between ring 3 that was outside the bruised region and ring 3 from the nonbruised side. There was less red, more green, more blue, greater hue, less saturation and more intensity on the nonbruised side of the apples versus the bruised side ($p < 0.01$). From the data collected it was not possible to tell if this difference was an interaction from the bruising process in good tissue adjacent to bruised tissue or was a natural color variation. NIR, green, red and hue (Figure 5a) were more effective for discriminating bruised from nonbruised areas (largest t-values for comparison of rings 2 and 3 at the bruise location). Large variations in surface reflectance for blue, saturation, and intensity reduced their discriminating ability (Figure 7b). Red, green and hue (Figure 8b-d), unlike NIR (Figure 8a), did not show the increase in reflectance for bruised tissue with storage time. These features could be used to form a discriminate function for identifying bruising on stored Golden Delicious apples.

Cluster Segmentation - Evaluation of Algorithms.

In recent years, image processing for agricultural applications has been widely used in research and industry. Many of these algorithms trace the boundary of pixel clusters and determine their area.

Mean Pixel Value Difference
Large Minus Medium Ring

Mean Pixel Value Difference
Large Minus Medium Ring

Figure 7. Mean of the differences between nonbruised profile and the bruised profile (ring 3 minus ring 2) for: a) NIR, red, green, and hue. b) Blue, saturation, and intensity.

NIR Pixel Value Means

Red Pixel Value Means

Green Pixel Value Means

Hue Pixel Value Means

Figure 8. Mean of pixel values for ring 2 (bruised) and ring 3 (unbruised) for three storage dates after bruising for a) NIR, b) green, c) red, and d) hue.

Image processing algorithms were developed for building a database of physical properties of seeds (Cooper et al., 1985). A boundary chain code representation of a berry's profile was obtained in an attempt to detect stems in a binary image (Wolfe et al., 1985). An eight neighborhood chain code representation of a tomato's boundary was used by Sarkar et al (1985) as the feature for detecting shape. McClure et. al. (1987) started their boundary encoding algorithm with the last pixel in the center row of the scene. From this pixel an eight pixel neighborhood was searched in a clockwise direction to find the next white pixel on the boundary. The search continued until the

next white pixel was the starting pixel. Sapirstein et al. (1987) applied an eight pixel connected region that allowed edge following of cereal kernels for inspection and classification. Sites et al. (1988) used eight connectivity analysis to locate fruits on peach and apple trees. This analysis defined pixels to be connected if they had a common vertical, horizontal or diagonal boundary. Rehkugler et al. (1989) used a vector oriented contour following routine to size bruises on apples. In the same paper, an algorithm that located the median pixel in each cluster row and from there searches left and right for the edge of the cluster in that row was reported. The objective of this study was to develop a method to evaluate algorithm performance for cluster boundary identification and determine which identification algorithm, CLUSTER (Rehkugler's vector oriented), CENTROID (Rehkugler's median pixel) or BOUNDARY (eight connectivity), produced the most accurate results for the least amount of processing time.

Twelve test images consisting of 256 pixel by 256 columns were generated for testing. Eleven different cluster types or shapes were identified (Figure 9).

Figure 9. Eleven cluster types or shapes used to test the algorithms performance.

Each test image consisted of 10 identical clusters and each test image had a different cluster type. Clusters were black (grey level of 0) on a white background (grey level of 200). The 12th test image was a white background only. Each test cluster type was constructed with different geometric or spatial characteristics to test the ability of each algorithm to find the area and perimeter. Processing efficiency was measured in terms of processing time. Table 7 shows the area and 4-connectivity perimeter in pixels for each test cluster.

Table 7. Cluster shapes shown with the actual measured area and perimeter pixel with 4- and 8-connectivity.

Cluster Number	Measured area	4-connectivity	8-connectivity
1	116	32	44
2	390	138	173
3	392	136	172
4	152	78	84
5	108	32	44
6	116 x 2	32 x 2	44 x 2
7	232	60	84
8	232	64	90
9	376	128	156
10	416	119	145
11	388	120	150

The cluster area, perimeter, and processing time for each test image was recorded as data. The time to scan an image with no clusters was subtracted from the images of test clusters and the resulting time was divided by 10 to find the mean time per cluster.

All of the three algorithms correctly determined the cluster area in pixels. Differences between the measured 4-connectivity perimeter and the perimeter calculated by the three algorithms is shown in Table 8.

Table 8. The results for a t-test found no significant differences between the calculated perimeters for the three tested algorithms ($p > 0.2$).

Differences	N	Mean	Standard Deviation	Calculated t
CLUSTER	11	-1.286	3.068	-1.92
CENTROID	11	0.286	4.209	0.31
BOUNDARY	11	-0.857	2.056	-1.91

CENTROID was slowest algorithm, taking at least twice as long to process each cluster (Figure 10).

None of the algorithms handled clusters which had a pixel forming two different boundaries. These pixels are only counted as perimeter pixels once (test clusters 8, 9, 10, 11). CENTROID interpreted the island pixels in cluster 5 as perimeter pixels. BOUNDARY counted one of the two islands in cluster 5 as perimeter pixels because of the island's close proximity to the cluster's border. The results showed that the CLUSTER and BOUNDARY algorithms are not significantly different in performance or speed and either would be appropriate for analyzing apple bruises.

Figure 10. The time for each cluster type is shown for each algorithm.

Nonorientation System for Apple Defect Detection.

A feasibility study and preliminary design for an imaging system for non-oriented apples was undertaken (Real Time 3-D Image System, Master of Engineering Project by Wen-Chung Chen). The preliminary design employed 4 line scan cameras (a camera on each side of the apple) and appropriate lights,

a unit to detect incoming apples and scan the four cameras, and a data acquisition system.

The transport system was designed to cause the apples to pass the cameras in approximately 26ms. In order to obtain 75 scans of each of the 4 line scan cameras (64 photo-detectors), a scan rate of approximately 1850KHz was needed. At this frequency, line drivers were used for data transmission over long cable lengths and under electrically noisy conditions. Lenses (25mm, F1.8 with a 0.5mm lens extension), camera (Reticon LC600 C64-2) and lights (PAR-64 bulbs) were specified. This provided a camera system with a working distance of 10 inches, a depth of field of 2 inches, and a camera with a 1:3 microwatt² sec/cm² sensitivity. The lights needed to provide approximately 330,000 lumens for an assumed reflection rate of 30%. The data acquisition system selected was a DT2851 frame grabber board installed in an IBM-AT computer. Material, construction, and development costs were considered to high to attempt actual construction because of the reduced funding experienced by this BARD project and other research funding sources.

Time Effects and Storage Conditions on Watercore Detection:

Watercore is characterized by the filling of the large intracellular air spaces with fluid and does not generally alter the external appearance of the fruit until severe tissue breakdown occurs. Mild watercore has fluid around some of the 10 vascular bundles whereas severe watercore is characterized by the coalescing of the fluid. Currently, this damage is evaluated by visual inspection of sliced apple halves from a random sample.

Fluid filling the intracellular spaces alters the light scattering properties of apple tissue. For normal apple tissue, the presence of air spaces increases the optical path length through the fruit due to intense light scattering. Light scattering is reduced for watercore fruit and results in more energy being transmitted through the fruit (Birth and Olsen, 1964). An instrument that measured the optical-density difference at 760 and 810 nm was used to detect watercore (Birth and Olsen, 1964; Birth and Norris, 1965). This single point measurement was expanded into an area measurement by using a machine vision system (Throop et al., 1989, 1991).

Severity of watercore and elapsed time before inspection affect the ability to detect watercored fruit with light transmission techniques. Researchers have reported that mild watercore has a high probability of diminishing with time, while severely watercored fruit will probably exhibit internal breakdown (Marlow and Loescher, 1984; Myers, 1983). For apples placed in regular cold storage, light transmission levels decreased to undetectable levels with initial camera settings for all classes of watercore (Upchurch et al., 1991). However, it is unknown as to the effect of storage conditions, regular cold storage versus controlled atmosphere, on the light transmission properties of watercored fruit.

Over 200 Delicious apples were segregated into four watercore classes following the procedure described by Throop et al. (1989). Class assignment was based on the amount of light that was transmitted through the fruit. Measurements were made at Cornell University prior to overnight shipment to the Georgia Experiment Station. On arrival at the Georgia Experiment Station

Station, light transmission levels were measured with a machine vision system. Eighty-eight apples of varying watercore were placed in controlled atmosphere (CA) storage while another 88 fruit were placed in conventional cold storage. Temperature of all fruit were maintained at 4°C.

Light transmission levels were measured at 2, 4, 6, 10, 14, and 22 weeks into the study. Apples were positioned with the stem-calyx axis collinear to a 150 W incandescent light source. While illuminating the calyx-end of the apple, a CCD camera viewed the stem-end. The mean gray level within a window that was centered about the stem was an indicator of the amount of light that was transmitted through the fruit.

Anatomical evaluation of watercored and nonwatercored tissue was performed on each sampling date. After measuring the light transmission levels, a random sample of 10 apples were removed from each storage group and destructively evaluated for visual watercore. Moisture content of watercored areas as well as nonaffected tissues was measured by vacuum oven method. Anatomical evaluation was performed on selected tissues with a scanning electron microscope (SEM). Apple tissue samples were prepared for SEM evaluation by chemical fixation and cryo-fracturing (Kim and Hung, 1990).

Preliminary results indicated that the type of storage has an affect on the amount of light transmitted through the fruit. For both CA and conventional storage, apples with no watercore had low levels of light transmitted through the fruit. Apples with severe watercore may or may not have a high light transmission score. Transmission levels appeared to remain higher for the CA group compared to the conventional storage apples. Light transmission scores for CA stored apples were not significantly different from the conventional storage scores during the first 5 sample dates (November 5 to January 2). However, a significant increase in the light transmission score was exhibited for the period January 28 to March 23. At the end of the study, light transmission scores were near zero for both treatments.

Watercored tissue exhibited anatomical differences. Initially, cells within watercored tissue were elongated when compared to cells from nonwatercored tissue. This elongation of the cells became less pronounced as storage time increased in both CA and conventional storage. Although the light transmission levels decreased to undetectable levels by April 23, watercore was still evident in some fruit; however, the fluid around the vascular bundles had changed from a translucent to a cloudy appearance. Further work is needed to ascertain the effect of watercore on cell wall structure and the effect of time on the fluid in the tissue.

DESCRIPTION OF COOPERATION

Different aspects of automatic bruise detection were addressed by the cooperators on this project. Automatic bruise detection is a very difficult research problem, and there are several areas that needed to be investigated in both basic and applied research. There were physiological changes in the apple tissue that needed to be defined. Drs. Ruth Ben-Arie, Lillian Sonogo, and Nurit Flohr investigated basic physiological changes that occur when apple tissue is damaged and how these changes could be measured was a major part of their effort. The technique that has potential for automatic bruise detection

is image processing of near-infrared or color images. Limitations of near-infrared imaging as well as the problems with applying spectrophotometric results into a machine vision system were investigated by the Appalachian Fruit Research Station. In a parallel study at Cornell University, image processing algorithms were developed for distinguishing bruised from nonbruised regions in images of apples. Both near-infrared and color images were used.

Various forms of communication were used by the cooperators of this research project. Correspondence between the two countries was maintained with electronic mail (BITNET). A minimum of three meetings per year were held between Appalachian Fruit Research Station and Cornell University to review the progress of each station, and plan the following year's work.

EVALUATION OF RESEARCH ACHIEVEMENTS

The overall goal of the project was to develop a photometric measurement technique for detecting defects on apples and investigate physiological changes in damaged tissue that might lead to alternative sensing techniques. Most of the research effort concentrated on characterizing the anatomical and physiological changes that occur in techniques for detecting bruises. During the project, it became apparent that color imaging has more limitations than near-infrared imaging for detecting bruises on Golden Delicious apples. However, color imaging appears to present an advantage in detecting bruises that are over 1 month old. Time or age of the bruise is a very limiting factor for detecting bruises with near-infrared imaging. Near-infrared imaging detected bruised after 24 hours on both Red Delicious and Golden Delicious apples. For automatic bruise detection, the system must adapt and inspect for various age bruises. The physiological and anatomical studies may provide some explanations as to the changes in light reflectance experienced in these studies. To understand the changes in light reflectance over time and between varieties, there is a need for an engineer and physiologist to work very closely in relating the light interaction with the tissue condition. No effort was given toward the development of a prototype system; however, design considerations and limitations of an inspection system have been well defined by this project.

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