ABSTRACT

Title of Document: WHOLE SURFACE IMAGE RECONSTRUCTION FOR MACHINE VISION INSPECTION OF FRUIT

Daniel Young Reese, Master of Science, 2008

Directed By: Associate Professor, Y. Martin Lo, Nutrition and Food Science

Automated imaging systems offer the potential to inspect the quality and safety of fruits and vegetables consumed by the public. Current automated inspection systems allow fruits such as apples to be sorted for quality attributes such as weight, color, and size based on imaging a portion of the surface of each fruit. However, to ensure the inspected fruits are free of defects and contamination, the whole surface of each fruit must be imaged. The goal of this project was to develop an economical module capable of providing whole surface imaging of apples using mirrors and a single camera. Different configurations of flat and concave mirrors were examined and their ability to approach 100% of an apple's surface were characterized and compared. Specific configurations of two, four, or six parabolic concave mirrors were found capable of imaging an entire apple surface at desired image size for inspection without image distortion. This imaging module developed could be integrated into existing automated inspection systems to leverage the effectiveness of food safety inspection.

.

WHOLE SURFACE IMAGE RECONSTRUCTION FOR MACHINE VISION INSPECTION OF FRUIT

By

Daniel Young Reese

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2008

Advisory Committee:
Professor Y. Martin Lo, Chair
Dr. Alan Lefcourt
Dr. Moon Kim
Professor Mickey Parish

Acknowledgements

I would like to thank all my committee members for their various supportive contributions and inputs to my thesis project. I appreciate the direction and guidance provided by Drs. Alan Lefcourt and Moon Kim at the Food Safety Laboratory at the USDA-ARS Beltsville Agricultural Research Center (BARC). In addition, I would also like to thank Dr. Mickey Parish for his support (and without a chance meeting with him, I would not find myself at the University of Maryland) and recognize Dr. Martin Lo as a source of encouragement, motivation, and creative inspiration as my major professor and adviser.

I also would like to thank my other colleagues and friends at the Food Safety Laboratory at the USDA (including Frank Gwodz who provided much help in constructing the imaging system) and my fellow graduate students in Dr. Lo's group in the Department of Nutrition and Food Science at the University of Maryland: Dr. Sanem Argin, Ansu Cherian, Peter Machado, Avani Sanghvi, Karen Silagyi, Pavan Kumar Soma, Patrick Williams, and I Chang Yang,

I thank the Food Safety Laboratory in the Agricultural Research Service at the U.S. Department of Agriculture for this opportunity to work on this project. I also acknowledge the Department of Nutrition and Food Science at the University of Maryland for providing support during this project.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Automated imaging systems offer the potential to expedite inspection of the quality and safety of fruits and vegetables consumed by the public. Recent outbreaks of foodborne illness in the U.S. remind the public of the food safety risks in consuming produce. For instance, unpasteurized apple juice and cider have been repeatedly linked to *Escherichia coli* O157:H7 contamination (FDA, 1999), mainly because apples with defects such as diseased or fungal contaminated surfaces and open skin cuts and bruises may become sites for microbial attack (Fatemi et al., 2006). In addition, apples that have fallen on the ground can be contaminated with fecal material. Current automated inspection systems allow fruit such as apples to be sorted for quality, namely by physical characteristics such as weight, color, shape, and size. To date, automated defect and contamination detection methods, on the other hand, are not commercially available due to challenges in whole surface imaging, especially concave areas on fruit surfaces.

A variety of setups for whole surface imaging has been attempted and reported in the literature (Li et al., 2002; Bennedsen et al., 2005; Imou et al., 2006); unfortunately, none allow for whole surface imaging that is commercially feasible. At present, sorting of fruits for surface defects is mainly done by manual inspection (Bennedsen et al., 2005). Thus, there is pressing need to develop an effective and economical method for automated whole surface imaging of fruits. This study examines the use of mirrors for whole surface imaging of an apple using a single camera.

Chapter 2: Literature Review

Food Safety and Fresh Produce

Foodborne pathogens

Each year there are an estimated 76 million cases of foodborne illnesses, of which 5,000 are fatal (Mead et al., 1999). Some of the most frequent foodborne pathogens associated with fresh produce include *Salmonella* and *Escherichia coli* O157:H7. Outbreaks linked to *Campylobacter jejuni* have been found for contaminated melons and strawberries (CDC, 1993) while *Listeria monocytogenes* food recalls have been associated with lettuce and fresh-cut fruit (FDA, 2006); however, these pathogenic bacteria are primarily associated in outbreaks with meat and poultry products. *Salmonella* and pathogenic *E. coli* were the two largest foodborne pathogens linked to fresh produce from 1973 to 1997 (Sivapalasingam et al., 2004, Abadias et al., 2008) with *Salmonella* leading to 2 to 4 million cases of illness annually (FDA, 2001). In recent years, there have been numerous deadly human infections caused by *E. coli* O157:H7. In the early 1990s, hundreds were sickened and several deaths were caused by contaminated ground beef and hamburger patties (CDC, 1993). The Center for Food Safety and Applied Nutrition (CFSAN) at the U.S. Food and Drug Administration (FDA) reports between 20,000 and 40,000 cases of illness related to *E. coli* infection annually (FDA, 2001). The infectious doses of *Salmonella* and pathogenic *E. coli* can both be very low (depending on the strain of the bacteria): as low as 15 to 20 *Salmonella* CFU (colony-forming units) can cause illness (FDA, 2006) and just 10 to 100 CFU of *E. coli* O157:H7 can cause illness (Jay et al., 2005). Produce that has been implicated in *E. coli* infection include spinach, lettuce, alfalfa sprouts, and apple cider (CDC, 2006; CDC, 1996; FDA, 2007). Recently, at least 205 cases of illness and three deaths were linked to spinach found to contain *E. coli* (FDA, 2007). Some foodborne pathogens associated with fresh produce outbreaks in the U.S. in recent years are summarized in Table 1.

Table 1: Recent outbreaks and recalls due to pathogens in fresh and fresh-cut produce

Microorganism	Target	Outbreak (deaths)	Year	Reference
Salmonella				
Baildon	Tomatoes	86 cases	1999	CDC, 1999
***S.* Chester**	Cantaloupe	247 cases (2 deaths)	1990	CDC, 1990
***S.* Javiana**	Tomatoes	176 cases	1990	Jay, 2005
***S.* Montevideo**	Tomatoes	100	1993	Jay, 2005
***S.* Muenchen**	Orange juice (unpasteurized)	207 cases	1999	CDC, 1999
***S.* Oranienburg**	Fruit salad	41 cases	2006	CDC, 2006
***S.* Poona**	Cantaloupe	47 cases	2000	CDC, 2000
***S.* Saphra**	Cantaloupe	24 cases	1997	CDC, 1997
Salmonella	Spinach	Recall, no reported illnesses	2007	FDA, 2007
***E. coli* O157:H7**	Apple juice (unpasteurized)	66 cases, (1 death)	1996	CDC, 1996
	Spinach	205 cases, nationwide (3 deaths)	2007	FDA, 2007
	Alfalfa Sprouts	108 cases	1997	CDC, 1997
	Romaine, green leaf, & butter lettuce	Recall, no reported illnesses	2007	FDA, 2007
Shigella sonnei	Fresh parsley	443 cases	1998	CDC, 1998
Campylobacter jejuni	Melons & strawberries	48 cases	1993	CDC, 1993
Listeria monocytogenes	Fresh-cut (cantaloupe, honeydew, red grapes, pineapple, watermelon or strawberries)	Recall, no reported illnesses	2006	FDA, 2006

Smaller foodborne pathogen outbreaks involving produce items have also been linked to *Cyclospora cayetanensis*, G*iardia lamblia*, as well as several others (Sivapalasingam et al., 2004).

The public remains at risk from foodborne diseases from produce that may be exposed to direct or indirect contact with animal feces and is not subsequently treated to kill all pathogenic bacteria. Raw, untreated bovine and ovine manure have been shown to harbor pathogenic *E. coli* bacteria that can survive for up to 70 days (Kudva et al., 1998). These bacteria are frequently found in the intestines of sheep, cattle, and deer. Apples have the potential to be contaminated with *E. coli* bacteria if the fruit comes in contact with fecal material. The FDA further states that:

> animal feces can contaminate apples either directly by contaminating apples dropped on the ground or indirectly by contaminating workers, crates used to haul apples, water used for spraying and irrigating orchards, and possibly by being carried by the air (FDA, 1996).

The source of a 1996 outbreak of pathogenic *E. coli* in unpasteurized apple cider in Connecticut was never definitively proven, but “drop” apples (apples used in juice that had fallen and been picked off the ground) were the presumed source of *E. coli* contamination (Hilborn et al., 2000). The drop apples were likely to have come in contact with animal feces (such as cow or deer) on the ground. Evaluation of the outbreak determined that washing and brushing apples was not sufficient to prevent cider contamination. Also in 1996, the CDC found unpasteurized apple cider to be the source of another *E. coli* outbreak in western states resulting in at least 66 confirmed illnesses and one death (CDC, 1996; FDA, 1999). Odwalla brand juices were found to contain the pathogen and over 1000 units were pulled from stores. The exact source of the contamination was never pinpointed, though sanitation procedures were found to be deficient in the production plant and contaminated apples were possibly used for juice.

Food Safety Monitoring

Several U.S. government agencies are charged with overseeing, monitoring, and reporting food safety-related issues. The U.S. Department of Agriculture (USDA) operates the Food Safety Inspection Service (FSIS) that inspects and regulates meat, poultry, and egg products. The FDA is responsible for regulating shellfish, milk, and retail food. The Centers for Disease Control and Prevention (CDC) report, track, and investigate illness outbreaks. These federal agencies in cooperation with the industry and state and local governments work to ensure the safety of the nation's food supply. It is through the FDA and FSIS that food product recalls can be initiated, though companies can initiate product recalls without government pressure. With fresh fruits and produce, it is often difficult to pinpoint where contamination occurred in an illness outbreak as demonstrated in the aforementioned *E. coli* outbreak in Connecticut. In addition, fresh fruits have relatively limited shelf life. *E. coli* and *Salmonella* have incubation periods of up to four and two days, respectively (Jay et al., 2005). By the time symptoms are present in a person, the food may have been discarded, making it extremely difficult to track the source of outbreaks.

Apple Consumption

Among the American public, apples remain a popular choice for fruit consumption (both processed and unprocessed forms) and a significant part of the American diet. The Economic Research Service (ERS) of the USDA estimates that nearly 45 pounds of apples (fresh and processed) are consumed per person in the US each year with consumption of fresh whole apples at 18 pounds (2005). Apples are consumed in various processed forms (such as apple cider or applesauce) and non-processed forms (fresh varieties found in restaurants and grocery stores). In 2007, the USDA forecasted apple production at 221.1 million bushels—of which 141.1 million bushels would be fresh products and 78 million bushels would be processed products. Fresh-cut packaged fruit are increasingly popular due largely to its perceived health benefits (compared to conventional snack foods) and convenience. Sales of fresh-cut fruit grew 15.7 percent from 2005 to 2006—representing $242 million in the first quarter of 2006 alone, according to the fresh-cut trade association (Fresh Cut, 2006). One notable example reflecting this trend is that many fast-food chains have recently replaced French fries in kids' meals with apple slices to provide healthier options.

Mode of Contamination Transfer and Sources of Contamination

Most processed apple products such as applesauce and apple juice undergo thermal processing to kill pathogenic microorganisms. In recent years, processed apple cider has been found to be susceptible to *E. coli* contamination but in these cases the cider was not pasteurized. Fresh-cut packaged fruits generally do not undergo such rigorous processes due to quality degradation of the fresh products. Fresh-cut fruit can be minimally treated, such as with washes and modified atmospheric packaging. Nevertheless, fresh-cut packaged fruit may still pose a risk of transmitting foodborne pathogens, for instance, by coming in contact with contaminated cutting equipment. Little information about microbial contamination of fresh-cut fruits or vegetables has been published (Abadias et al., 2008). For some whole fresh produce, possible routes of contamination include contact with animal fecal material as well as improper handling procedures from workers that pick and pack fruit. Contamination can also come from irrigation water or dust containing fecal material. The sources of bacterial contamination are summarized in Table 2. Contamination can be reduced if interventions are in place to reduce risk at different points in the process of harvesting, transporting, sorting, and packing apples (see Figure 1 and Table 2). Such a risk reduction plan could operate similar to a Hazard Analysis Critical Control Points (HACCP) management scheme, a preventative, proactive system with various points of control designed to reduce or eliminate hazards to ensure production of microbiologically safe foods. However, practical difficulties exist in establishing HACCP plans for the entire apple processing, since it is impossible to set up the control limits in the open field. Establishment of HACCP is only feasible in the enclosed processing facilities to cut or process apples into small pieces or juice products. Therefore, an effective inspection system is urgently needed to detect points of contamination as early as possible in the processing scheme.

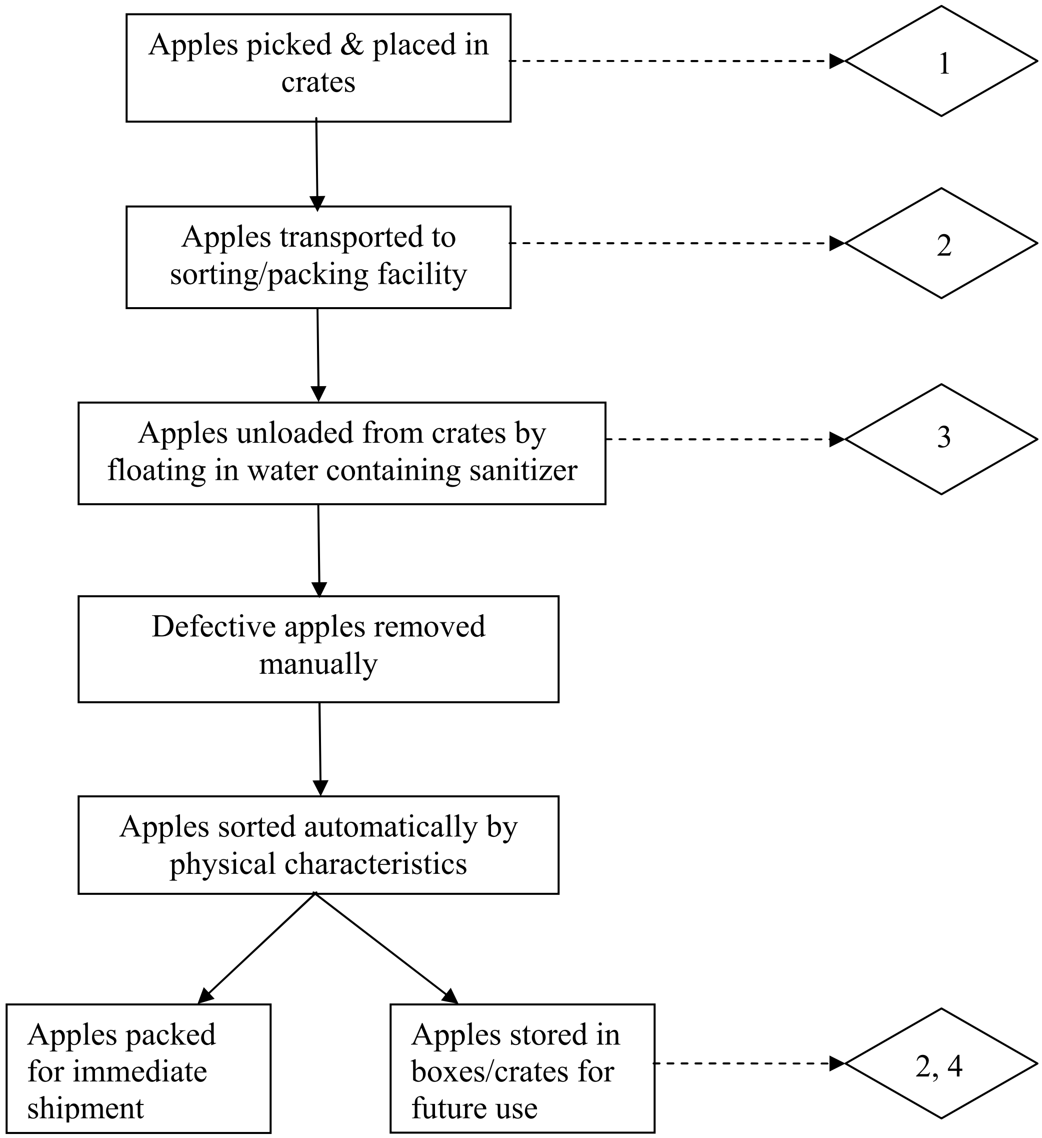


Figure 1. Process diagram for typical apple processing. Numbers in diamonds reference stages in Table 2 (page 10).

Table 2. Actions to reduce microbial risks during post-harvesting of fruit.

Stage	**Vulnerability**	**Method for microbial reduction**	**Remarks**	**Reference**
1. Harvesting	Contamination from contact with animal feces, human handling	Prevent animals from entering orchard; GAPs (employees hygiene)	Good Agricultural Practices (GAPs) promote food safety from "farm to table" and includes proper worker hygiene in reducing contamination risk. Apples that are dropped may come in contact with animal feces. Crates set on the ground and then stacked can contaminate.	Cornell GAPs Wireman et al., 2001 Fatemi et al., 2006 Kaushal & Sharma, 1995
2. Transportation to packing facility	Contamination from field dust (containing manure)	Cover fruit	Orchards adjacent to fields that are fertilized with manure may be at increased risk since fecal material can be blown on to apples and settle in the stem area or other defect areas of the apple	Wireman et al., 2001
3. Washing	Cross-contamination in water stream	Sufficient concentration (50 ppm) of chlorine monitored several times per day; water pH 6.5 – 7.5 to keep Cl_2 active	Chemical poses potential toxicity: prolonged exposure to chemical is an irritant to workers	Abadias, 2008; Cornell GAPs
4. Storage	Microbial growth temperatures; relative humidity (RH)	Cold storage, controlled atmosphere (CA):low O_2, high N_2,	Temp.= -1 to 4°C : Slow or inhibit microbial growth for some pathogens, Controlled Atmosphere: inhibit ripening, %RH= 90-95 (RH too low dehydrates fruit; RH too high results in increased decay)	Reed, 2003

Technologies to Reduce Microbial Risks

When consumed fresh, fruits inevitably bear the risk of introducing foodborne illness via contamination, since all fruits are subjected to certain degrees of handling and/or processing (Beuchat and Ryu, 1997). Even if the contamination rate on apples is very small, the risk may be relevant due to the high consumption rate of apples. Once an apple is contaminated, it is difficult to remove 100% of the contamination since most conventional washes and sanitizing methods cannot reduce microbial populations by more than 90 to 99 percent (Sapers, 2001). Chlorine and sodium hypochlorite are commonly used as sanitizers since they are widely available and inexpensive (Xu, 1999). A minimum concentration is required for the chemicals to be effective against bacteria. For example, the minimum concentration for chlorine is 50 ppm and the water must be kept at a pH of 6.5-7.5 to keep the chlorine active (Abadias, 2008). Ozone has been shown to be an effective sanitizer, killing bacteria faster than chlorine. In addition, it decomposes to oxygen whereas chlorine sanitizer has chemical by-products. Ozone, like chlorine, at high concentrations is harmful to workers. However, sanitizers do not remove all contamination from fruit. A recent study found no significant difference between washing fresh produce with sanitizers (used in the home) and simply using tap water (Kilonzo-Nthenge et al., 2006; NPR, 2007).

Modified atmospheric packaging (MAP) is used in the fruit packing industry (specifically in storage). MAP minimally affects the product. Packaging atmosphere is altered, for example to 4% O_2, 10% CO_2, and 86% N_2, and water activity is lowered which leads to lower microbial populations (Martinez-Ferrer, 2002).

Irradiation can also be used to kill pathogens without heating; however, this technique is more invasive since higher doses of radiation can lead to fruit surface softening and vitamin loss (Murano, 2003). Methods for microbial reduction on fresh produce are given in Table 3 below.

However, one of the most effective ways to reduce pathogens on produce comes from adhering to Good Agricultural Practices (GAPs), Good Manufacturing Practices (GMPs), and HACCP prevention strategies (Parish et al., 2003). When GAPs and GMPs procedures are followed, the likelihood of contamination proliferation can be reduced in production processes. Once produce has been contaminated with pathogenic microorganisms, there is no one step that can eliminate pathogens without also adversely affecting the quality of the produce. Instead, prevention strategies can help reduce risk at each and every production step.

Table 3. Current and potential non-thermal actions taken to reduce microorganisms on fresh fruits.

Technology	Fruit	Effect (pros)	Limitations (cons)	Reference
Irradiation:				
-UV (UV light is used to break down microorganisms)	Apples	Reduced post-harvest pathogens Eliminate chemicals; delays ripening	Limited penetration of rays, cost	Bintsis et al., 2000 Lu et al., 1991
	Peaches	(same)		Lu et al., 1991
-Ionization (ionizing energy destroys microorganisms)	Strawberries Apples Apple juice	Reduced decay Delayed growth/destruction of pathogens without heating No alteration in flavors	Low consumer acceptance, softening of fruit surface, vitamin loss	Thayer & Rajkowski, 1999 Murano, 2003
Modified atmospheric packaging (MAP)		Maintain sterility, clear view of product, little or no need for chemicals	Finding plastic film with appropriate permeability; added cost; temperature control required; specialized training and equipment necessary	Phillips, 1996
	Apples (slices)	Retard textural and flavor changes; reduce browning		Lakakul et al., 1999
	Apples	Long-term storage		Lakakul et al., 1999
	Mangoes, pineapple	Reduce waste; extend shelf life; minimally affects product; lower water activity led to lower microbial population (under 4% O_2, 10% CO_2, 86% N_2)		Martinez-Ferrier et al., 2002
Sanitizing				
-Chlorine (wash)	Fruits	Widely available, inexpensive Removes dirt	Limited effect on killing bacteria Residual by-products of chlorine	Abadias, 2008
-Sodium hypochlorite (wash)	Fruits	Most widespread disinfectant	Limited effect on killing bacteria	Abadias, 2008
-Neutral electrolyzed water	Fruits, fresh-cut vegetables	As effective as sodium hypochlorite; offers safer and easier method for disinfecting	New technology, not in commercial use	Abadias, 2008
-Ozone	Fruits, fresh-cut vegetables	Kills bacteria faster than chlorine; 1.5 times stronger than chlorine; Decomposes to oxygen; slows ripening process	Harmful at high concentrations and extended durations of time	Xu, 1999; Achen & Yousef, 2001

Defects and Food Safety

Microbial growth can be accelerated inside defects such as lesions, cuts, and bruises on the fruit surface (Fatemi et al., 2006). When fecal material comes in contact with defect sites of an apple (such as cuts and punctures) conditions are favorable for growth of pathogenic bacteria such as *E. coli* O157:H7 (Fatemi et al., 2006). This is doubly problematic in that pathogenic cells once internalized in fruit not only may grow more rapidly but are also less likely to be affected by sanitizers (in contrast to pathogens that can be killed or washed away on the surface of the fruit). Also, fruits suffering from other disease such as mold offer sites that are favorable for pathogenic bacterial growth. These diseased areas on fruits may reduce acidity at the site (a natural barrier to microbial growth) and thus create favorable growth conditions for pathogenic microorganisms.

Existing Automated Processing Systems

Machine Vision

Machine vision is increasingly used for automated inspection of agricultural commodities (Brosnan and Sun, 2004; Chen et al., 2002). Research results suggest that it is feasible to use machine vision systems to inspect fruit for quality related problems (Bennedsen and Peterson, 2005; Brosnan and Sun, 2004; Throop et al., 2005). For fruit such as apples, commercial systems are available that allow sorting based on physical characteristics like weight, size, shape, and color. Automated fruit grading, standards assigned to fruit based on exterior quality, is also possible with machine vision (Leemans et al., 2002). Commercial sorters frequently use a conveyor system with either shallow cups (each cup holding one apple as it is moved) or bi-cone rollers that allow apples to rotate while moving along the conveyor (Figure 2). To be considered commercially applicable, automated systems must be able to handle fruit at rates of at least 6-10 fruit per second (Throop et al., 2001).

Figure 2. A Compac™ apple sorter. Courtesy of Compac, Inc., Visalia, CA.

A camera or cameras above the conveyor are commonly used to capture images in these systems, sometimes in conjunction with mirrors below the fruit. The rotation of apples produced by bi-cone rollers allows for the imaging of multiple aspects of each apple's surface by using two or more cameras spaced apart along the conveyer. This approach has not been proven to be viable for defect detection for a number of reasons, including non-uniform rotation due to differences in apple sizes and frequent bouncing due to non-uniform shapes.

Currently, there is no imaging process commercially used to detect defects or contamination due to lack of a method for imaging 100% of the entire surface of individual fruit. Thus, manual sorting remains the primary method for removal of apples with defects (Bennedsen & Peterson, 2005). Human error in sorting for defects may easily occur from worker fatigue and task-repetitiveness. Whole surface imaging can play an important role in this commercial process if accurate identification is achievable to allow for the removal of defective fruits that pose a threat of harboring foodborne pathogens.

Stem and Calyx

Stem and calyx areas present challenges for image acquisition and analyses due to their concave shapes. To image the entire surface requires sufficient perspectives to guarantee that cameras or mirrors can "see" inside these regions. A number of studies (with varying degrees of success) have looked at different approaches to image these areas (Yang, 1992; Campins et al., 1997; Wen and Tao, 2000). Machine vision systems may detect the stem and calyx areas as defects unless their location is known (Throop et al., 2001). This issue has been addressed by researchers by either having sensors look for both defects and stem/calyx regions as the fruit moves or imaging fruit that is oriented (position of stem/calyx regions is known) in hope of eliminating the need to search for those regions (Throop et al., 2001). However, no satisfactory stem and calyx orientation system has yet been found to be economical (Bennedsen & Peterson, 2004).

Furthermore, the stem on top of the apple is originally attached to the tree and the calyx is a natural opening at the bottom of the apple that was once the flower part of the fruit. These areas are likely to have greater contamination for several reasons. The stem area of an apple hanging from a tree allows for foreign materials to collect (such as blowing dust that may settle near the stem). The dust may come from nearby fields that have been fertilized with raw untreated cattle manure. In addition, microorganisms can enter the natural openings of apples as well as cut surfaces (Fatemi et al., 2006; Mendonca, 2005). Fatemi et al. also found that open calyces allowed greater pathogenic bacterial penetration than did closed calyces (2006).

Equally noteworthy is that washes have also proven ineffective at sanitizing these stem and calyx areas. For example, after apples were washed in water that contained bubbling ozone gas, counts of *E.coli* O157:H7 were reduced from the apple surface but not significantly from the stem/calyx (Achen & Yousef, 2001). In addition, stem and calyx areas are concave in shape and pose difficulties in imaging. To date, one of the greatest challenges in apple defect detection is distinguishing between the stem or calyx of an apple and actual defects (Throop et al., 2001). For this reason, some researchers seek alternatives where imaging the stem and calyx regions could be ignored. One such solution to this problem is to orient the apple prior to imaging so that the locations of the stem and calyx regions are known during imaging (Bennedsen et al., 2005). Imaging systems can then eliminate these concave areas since they are difficult to image and systems then direct efforts to the round surface of the fruit for quality imaging.

Fecal Contamination Imaging

Research results also indicate that it is feasible to use machine vision systems to inspect fruit for fecal contamination (Kim et al., 2002; Lefcourt et al., 2003; Lefcourt et al., 2005). Machine vision systems using fluorescent lighting have been able to detect fecal contamination on fruits such as apples and cantaloupe (Vargas et al., 2005). Such systems offer a non-invasive approach to detection of fecal material—a major food safety concern since feces from cows and deer have been shown to harbor pathogenic bacteria. However, these technologies are not currently used in commercial fruit sorting systems.

Whole Surface Imaging

A variety of setups have been proposed for imaging portions of the surface of produce. A common method for surface imaging involves moving fruit along a conveyor belt and capturing an image with one or two camera, but imaging that does not include 100% of the fruit surface is inadequate for defect and contamination detection. Li et al. (2002) reported an experimental setup to image four sides of an apple sitting in a shallow cup using two cameras (one above and one below the apple) plus two mirrors on opposite sides of the apple. The cup was bottomless to allow for a bottom view of the fruit. The apples moved in the cups along a sorting conveyor. The authors reported that 93% accuracy was achieved in distinguishing between defects and the stem-calyx with processing speed of 3 to 4 fruit per second. While this method allows much of the fruit to be imaged, portions of the surface are still blocked by the cup in which the apples sit. In addition, the system proposed by Li et al. assumes a vertical orientation of the apple's stem and calyx axis, but their experimental setup failed to address the need for a feeding or sorting system that is essential to ensure such orientation. If the apple stem-calyx axis was oriented in the cup at an angle less than 90º to the normal, the stem or calyx region may not be visible to the camera. Also, the use of a second camera diminished the desirability of this system since it significantly increased the cost.

A second method for imaging fruit while in motion involves apples rolling under a camera based on the design of Throop et al. (2001) and tested by Bennedsen et al. (2005). In their tests, a camera captured 6 images per apple at 30º rotation intervals.

This procedure captured half, or 180º, of the viewable surface. The whole surface could have been imaged. However, the test system was designed not to consider the stem and calyx regions due to the complexity of those regions. This is an obvious limitation of their imaging approach since it discarded areas that are highly susceptible to contamination.

Imou et al. (2006) proposed a method for reconstructing fruit shape from two-dimensional strawberry images using one camera with nine mirrors. The objective of their project was to develop a quick and inexpensive system to measure the shape of strawberries for quality grading of the fruit. Strawberries were placed stem-down (upside down) on a turntable with nine mirrors placed evenly (every 40º) around the fruit. A camera was located directly above the strawberry and images were acquired. The nine mirror images were combined to reconstruct the 3D shape of the strawberry. Imou and coworkers successfully reconstructed the strawberry shape but their method has several limitations. The top portion (or stem area of the strawberry) was not imaged since the strawberry was placed stem down on the turntable. Also, the complexity of using numerous mirrors makes this setup less attractive—especially if it is desired to implement such a system on a commercial level. Implementing this procedure in a commercial environment would be problematic.

Literature Summary

Concern for the safety of fruit (both fresh and processed) is increasing in importance—especially with the growth of fresh-cut fruit products. While the industry currently inspects fruit based on quality characteristics, there is no commercially-available whole surface imaging system for defect or contamination detection. Fruit with defects must be visually inspected and removed manually. An automated defect and contamination detection system could increase sorting speed (since human guessing would be eliminated) and reduce the chance for contaminated fruit remaining in processing (since human error would be removed). There are a number of proposed imaging techniques for fruit sorting; however, none have been able to provide whole surface imaging that is commercially viable. An automated whole surface imaging system can offer an economical method for sorting fruit for food quality and safety characteristics.

Chapter 3: Research Goal & Objectives

The ultimate goal of this project is to develop a non-invasive method for automated whole surface imaging of apples using mirrors and a single camera. Such a system would facilitate food quality and safety inspection that could help reduce the risk of foodborne illness associated with contaminated fruit. In order to achieve the goal, this project carried two specific objectives:

Objective 1: Investigate the effectiveness of various mirror types and configurations for whole surface imaging.

Objective 2: Optimize the imaging system when:

a. Apple orientation can be selected.

b. Apple orientation is random.

Chapter 4: Materials and Methods

Test Objects

Initially, a life-size plastic apple was segmented into four colored equal areas. It was segmented to check that the entire apple surface was imaged. Another plastic apple was symmetrically divided with a line and two dots were placed on it as another method for checking that the entire surface was imaged. Later, real apples (Red Delicious) were tested. These are depicted in Figure 3 below.

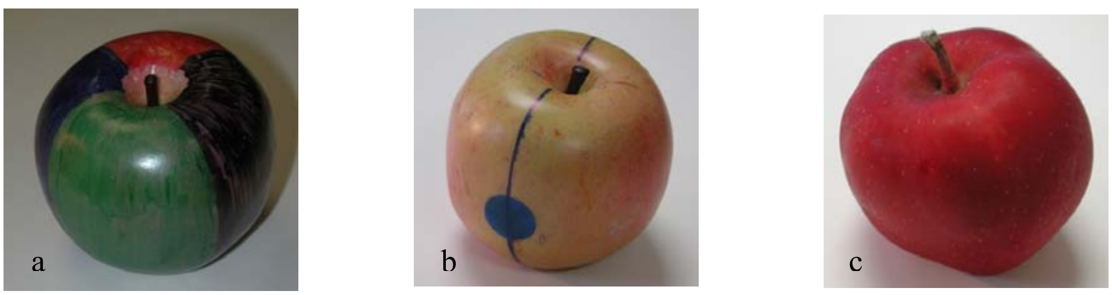


Figure 3: Test objects: a) Plastic apple colored segmented, b) plastic apple with line and dots, c) Red Delicious apple.

Imaging System Components

The system consisted of different sets of flat (17.8 x 12.8 cm), parabolic rectangular (3x magnification, 20.2 x 12.7 cm) and parabolic circular (5x magnification, 13.0 cm diameter) mirrors, a monochrome video camera (EC650, Prosilica; 640 x 480 pixels, non-interlaced, 90 frames per second), a fixed-focal length lens (Schneider Xenoplan, 17 mm, f/1.4), a 3 megapixel digital camera, and 4-gauge music wire. Two thin parallel wires (to allow for objects to be rolled along) were four cm apart and supported 19 cm above a steel optical bench (with internally threaded holes for mounting). The video camera was positioned 140 cm above the music wires. All support structures were aluminum structural framing. Halogen lighting (four 150 watt bulbs) reflected off a curved white surface (bright white sheets of paper) above the apple provided illumination. The setup is shown in Figure 4.

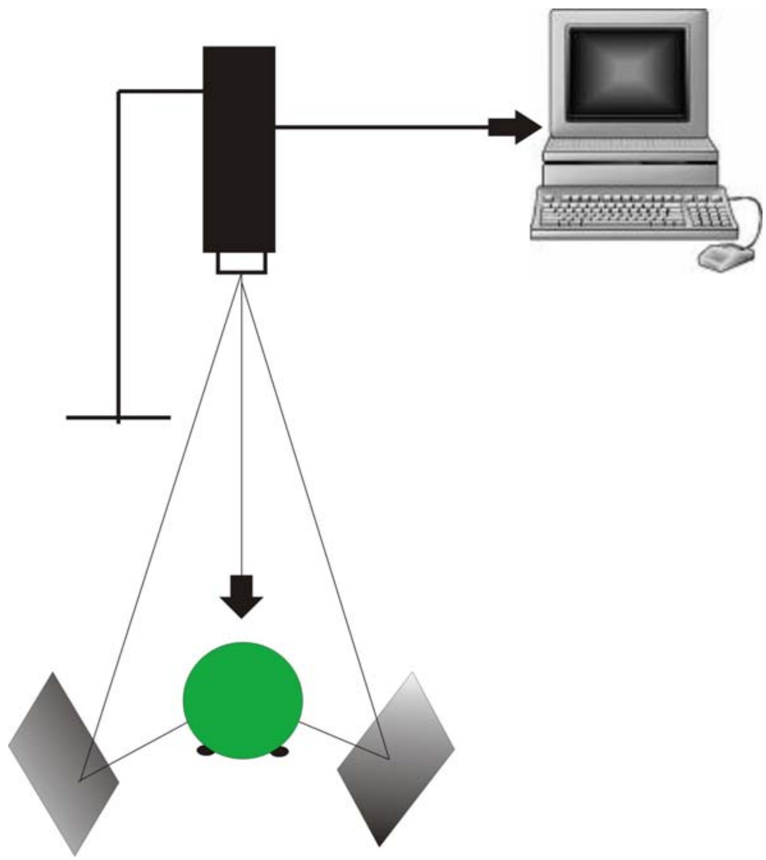


Figure 4: Experimental imaging setup. In this case, two mirrors are used to capture images of an apple's surface. The apple and reflected mirror images are captured from above using a monochrome video or color still camera.

Capturing Images

Mirrors were mounted at various positions, angles, and distances from the apple (which was suspended on the parallel wires). Positions and distances were empirically determined by adjusting the mirrors to optimize surface imaging. This test system allowed the user to visualize images and make adjustments on-the-fly as necessary. Figure 5 shows the proposed research model. Videos were acquired for the apples using a Visual Basic 6 program, and then still images were created from the video images. The image acquisition interface is depicted in Figure 6. Images were cropped for display. For images with two mirrors the native pixel dimensions were 560 by 180. Cropped images were then transformed to 600 dpi.

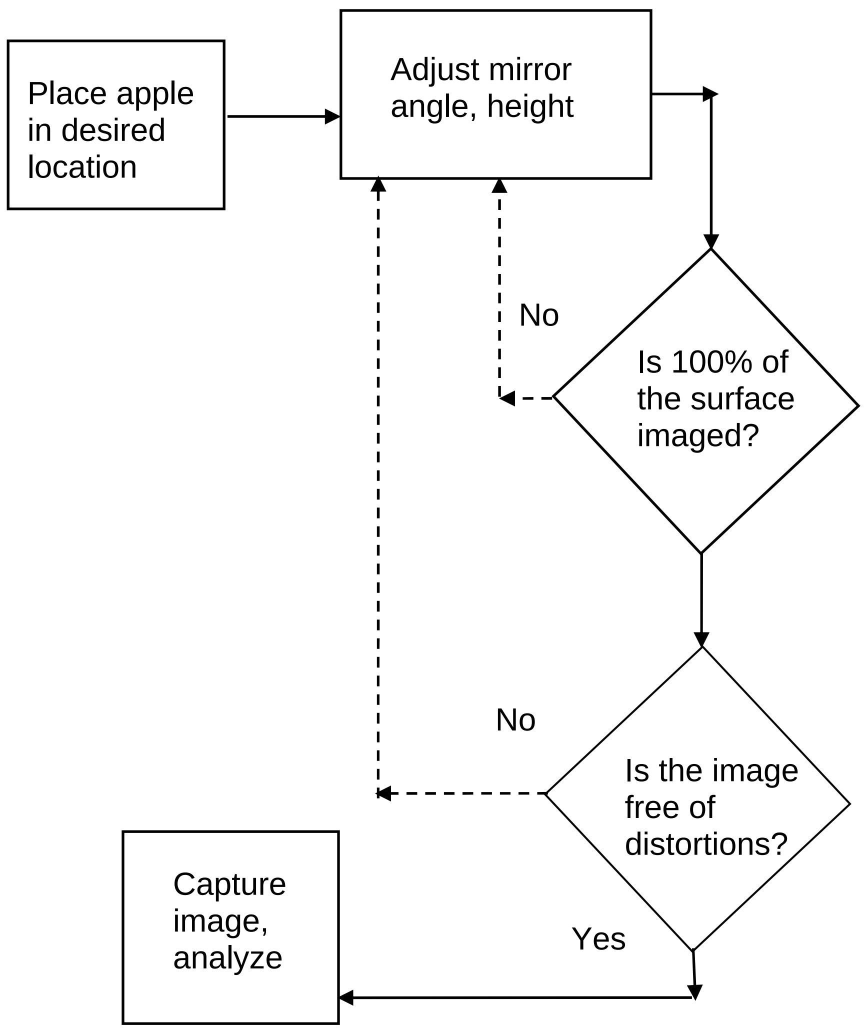


Figure 5. Flow diagram for experimental plan.

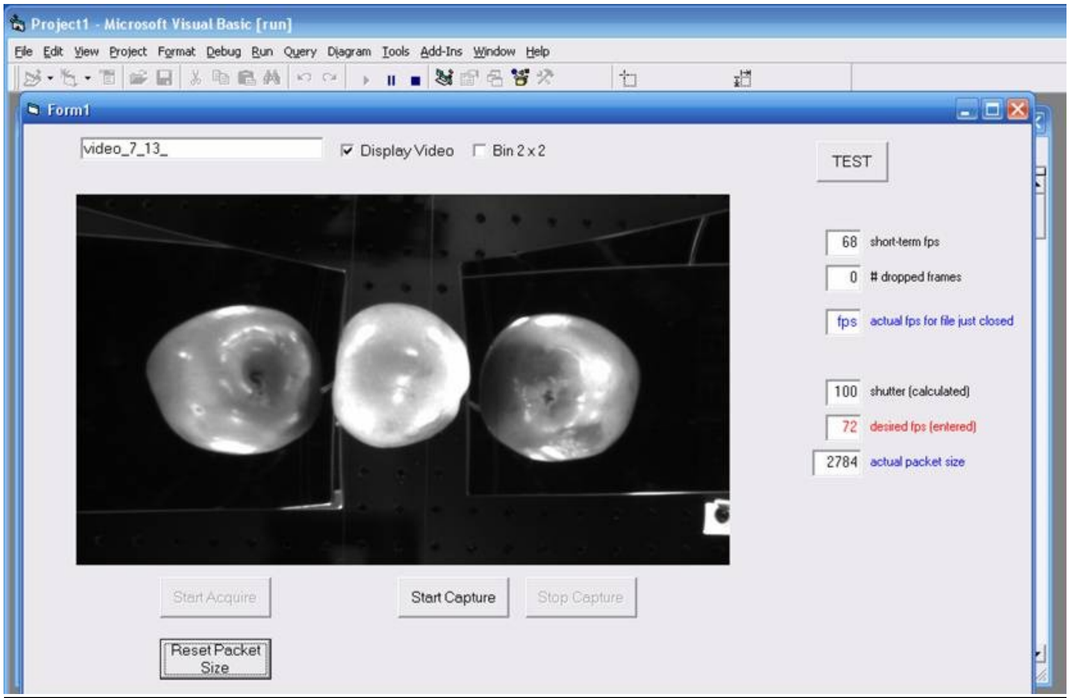


Figure 6. Image acquisition interface written in Microsoft Visual Basic 6 software.

Chapter 5: Results and Discussion

Image acquisition

Images of reflected surfaces were analyzed in terms of two potential imaging conditions: acquisition of a single image and acquisition of multiple images as the apple rolled through the imaging area on the two wires. These two approaches are shown in Figure 7 below.

In Figure 7a, a static method was given with a simple snapshot of the apple taken with two reflected images from two mirrors. In Figure 7b, an additional reflected image was added with an additional mirror. Figure 7c shows a dynamic model where initially a snapshot is taken of the apple and reflected images and additional images were captured as the apple rolled along the wires under the camera.

.

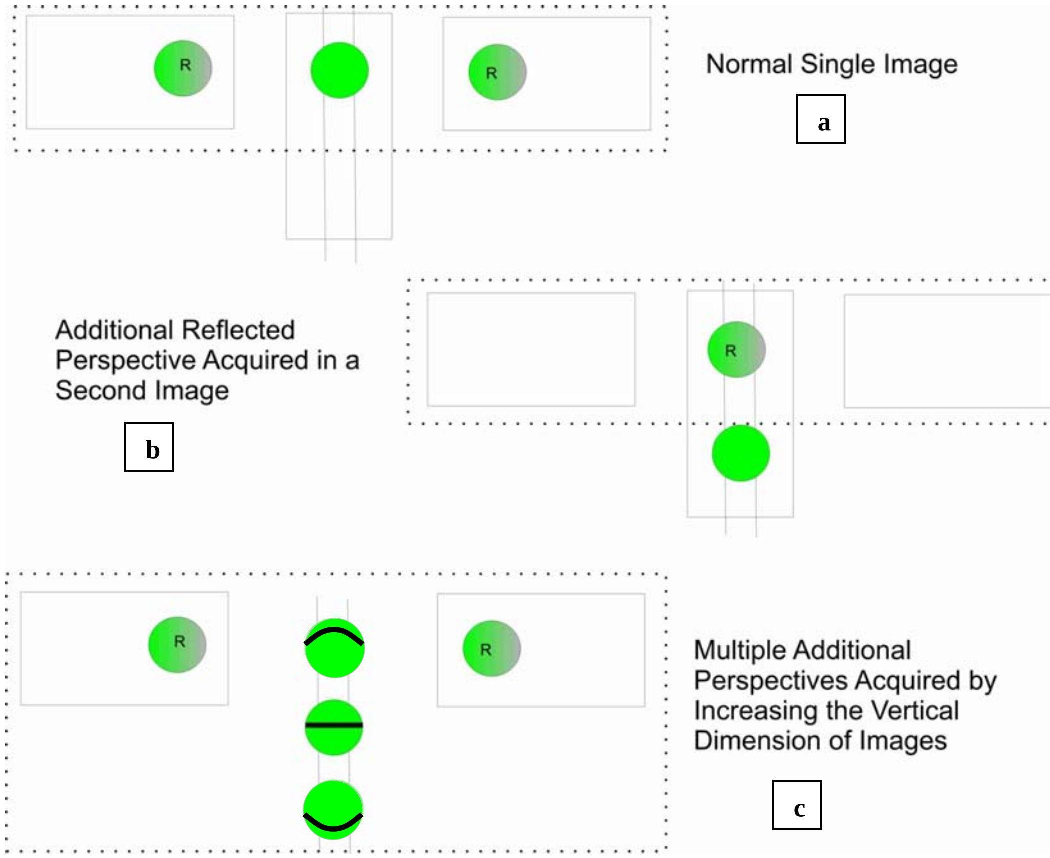


Figure 7. Modes of image acquisition. Circles with "R" indicate reflected images. "R" circles sit above mirrors. Dotted lines represent the imaging field. In 6c, the horizontal bar represents a point on the apple as it rolls under the view of the camera.

Flat Mirrors

The apples were initially imaged using flat mirrors. Mirror angle and distance from the apple were examined. First, the angle and location of test mirrors were modified so that direct and reflected images were separated by a minimal distance in acquired images. For each mirror inclination, effects on distortion were noted. Using results of these empirical tests, sets of test conditions for more detailed study were selected. For the detailed tests, the inclination of the mirrors and the vertical and lateral angles for apple locations were set using a protractor. As needed, small pieces of tape were added to the wires to hold an apple in a selected position. Additional mirrors were also used to determine optimal imaging of the apple. Images from imaging an apple with flat mirrors are shown in Figure 8.

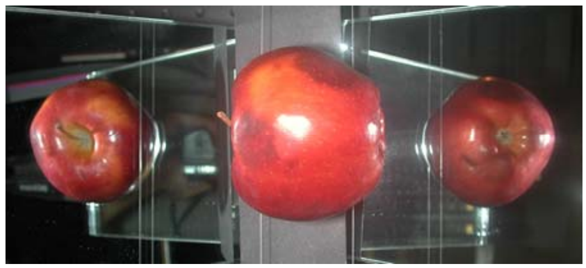


Figure 8. Images of an apple acquired with flat mirrors.

There are two types of flat mirrors: first and second surface and they are shown in Figure 9.

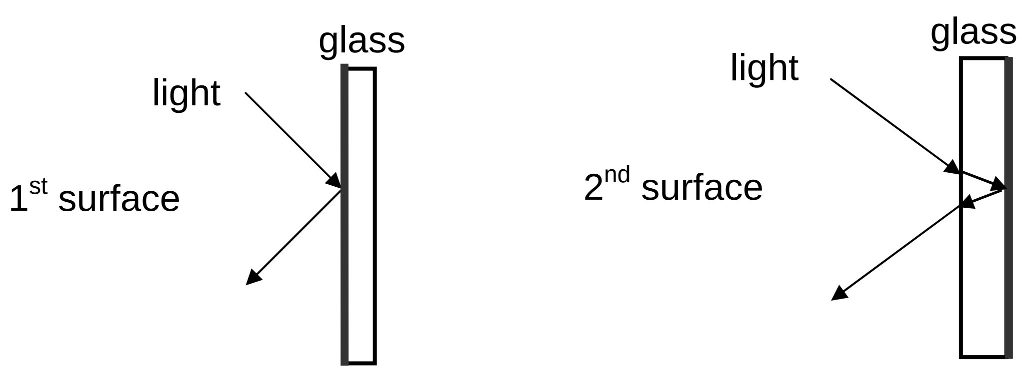


Figure 9. Diagrams for first and second surface flat mirrors.

In first surface mirrors, reflective coating is on the outer surface and incoming light rays immediately reflect off this first surface. Second surface mirrors are more commonly used (due to decreased cost) and have the reflective coating on the inside of the glass, or second surface. In this type of mirror, distortion can occur since the light ray must pass through the glass, reflect off the coating, and then exit through the glass. Flat mirrors do not provide magnification of the image.

Concave Mirrors

Certain types of concave mirrors show improvements over flat mirrors such as increased size and reduced image distortion. Table 4 lists various information regarding object and image locations and sizes for concave and convex mirrors.

Table 4. Images of objects from curved mirrors.

Concave				
Object	Image			
Location	Type	Location	Orientation	Relative Size
∞>Do>2F	Real	F<S<2F	Inverted	Reduced
Do=2F	Real	D_i=2F	Inverted	Same size
F<S<2F	Real	∞>D_i>2F	Inverted	Magnified
D_o=F		±∞		
D_o<F	Virtual	$\lvert D_i \rvert > D_o$	Erect	Magnified
Convex				
Object	Image			
Location	Type	Location	Orientation	Relative Size
Anywhere	Virtual	$\lvert D_i \rvert < \lvert F \rvert$, $D_o > \lvert D_i \rvert$	Erect	Reduced

where F is the focal point, D_o is the distance between object and mirror, D_i is the distance between image and mirror.
From: Hecht, 1998

The distance to the object, D_o, is less than the distance to the focus, F. The distance to the image, D_i, is taller than the object (magnified) and erect. The mirror equation is given as:

$$\frac{1}{D_o} + \frac{1}{D_i} = \frac{1}{F} \tag{1}$$

where D_i is the distance of the image to the mirror, D_o is the distance of the object to the mirror, and F is the focal length of the mirror.

Because the size of the convex imaged is reduced, convex mirrors were not studied. A larger image size (or magnification) is desired to increase image resolution. Magnification may be expressed as follows:

$$M = \frac{H_i}{H_o} = -\frac{S_i}{S_o} \tag{2}$$

where H_i is the height of the image and H_o is the height of the object and S_i is the distance of the image to the mirror and S_o is the distance of the object to the mirror (Hecht, 1999).

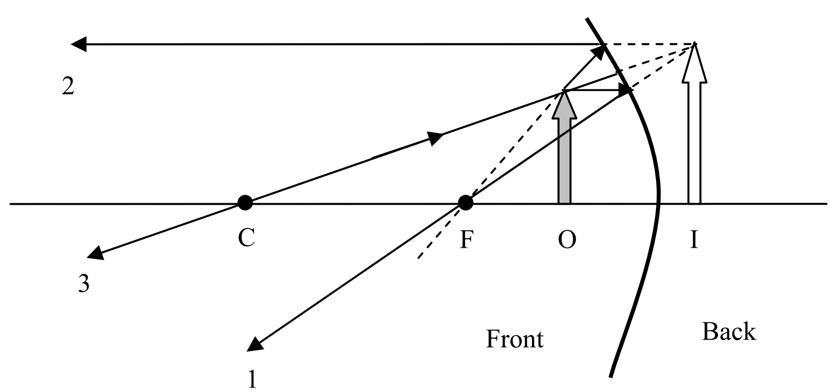


Figure 10. Concave mirror ray and image diagram for when the object stands close to the front of a concave mirror where *O* is the object, *F* is the focus, *I* is the image, and *C* is the center of curvature. Redrawn from: Serway & Beichner, 2000.

Figure 10 above shows a ray diagram for a concave mirror producing an upright, magnified virtual image. If the object, *O*, is placed to the left of *C*, an inverted, reduced real image is produced. If the object, *O*, is placed in front of a convex mirror, an erect, reduced virtual image results. A real image is one where light emanates from the image point, whereas in a virtual image, the light does not emanate from it (Tipler, 1999). The virtual image appears to be behind the mirror. However, the eye makes no distinction between virtual and real images.

One limitation of using mirrors includes distortion of the image, or a deforming of the image. There is some distortion seen with the common flat mirrors. Spherical concave mirrors also suffer from distortion, called spherical aberration (Hecht, 1998). The image appears blurred since light rays converge at different points. However, parabolic concave mirrors correct for spherical aberration by focusing parallel light rays to a single focal point (Serway & Beichner, 2000). Thus, parabolic mirrors show an improvement in light contrast over other mirrors due to a collimating effect—namely that light rays are made parallel after the light has reflected off the mirror surface. In Figure 11, all the rays converge at a single point producing a real image with uniform distribution of light and no spherical aberration.

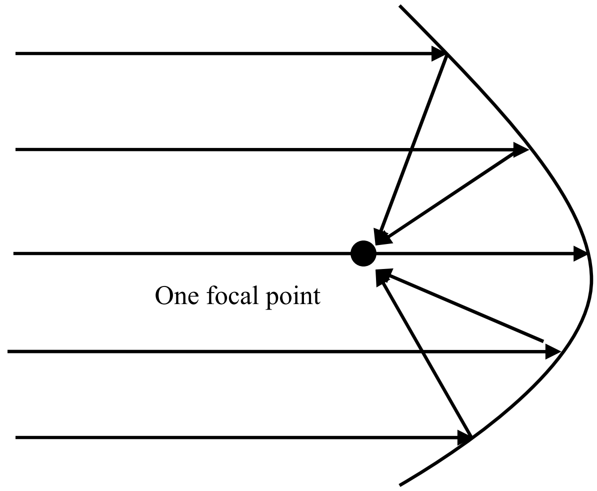
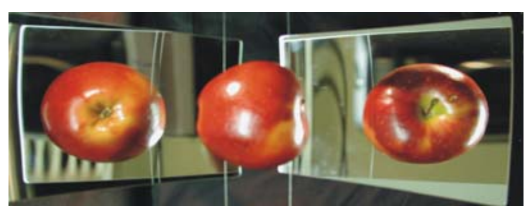


Figure 11. Ray diagram for a concave parabolic mirror with showing no spherical aberration since all rays converge at one focus. Redrawn from Hecht, 1998.

Parabolic Concave Mirrors

Data for parabolic mirrors demonstrated superiority over flat mirrors. Figures 12a and 12b show a comparison of images obtained from flat versus concave mirrors, respectively.

a.



b.

Figure 12. Comparison of images from flat (a) versus concave (b) mirrors.

The images from the flat mirrors in Figure 12a are smaller than the images produced using concave mirrors (with 3x magnification) in Figure 12b. Images from the parabolic mirrors are also clearer. For the best utilization of camera resolution, the parabolic concave configuration was more efficient than the flat mirror configuration due to magnification of reflected images from the parabolic mirrors. This result was confirmed by calculations of the image areas that represented useful information (Table 5). For example, the reflected apple images in Figure 12 represent 12.9% and 17.0% of the image area for the case of flat or parabolic mirrors, respectively. To accomplish this analysis, image pixels were converted to black pixels with white backgrounds. Black pixel area was compared to the white background area (Figure 13) using a routine written in Microsoft Visual Basic 6. The imaging area was examined in terms of a normalized 640 by 480 pixel resolution, and the same horizontal resolution with the minimum vertical resolution necessary to capture all useful information.

a b

Figure 13. Imaging area comparison between flat and concave mirrors. In 13a, area is given for the apple image plus two reflected images from flat mirrors. In 13b, area is shown for the apple image plus two reflected images from concave mirrors (which are larger than in 13a). In both sets, the bottom left circle is the imaged apple silhouette while the two upper silhouettes are the reflected images.

Table 5. Percentage of imaging area with useful information as a function of the number and type of mirrors used. The image area is standardized to 640 by 480 pixels.

Mirrors	Resolution	Reflected Images	All Apple Images
Full CCD usage			
Flat (2)	640 x 480	12.9%	22.7%
Concave (2)	640 x 480	17.0%	24.4%
Minimum necessary vertical CCD resolution			
Flat (2)	640 x 236	27.9%	49.3%
Concave (2)	640 x 191	43.4%	62.5%

Mirror configurations

Figure 14 shows the two mirror inclinations of 25° and 40°. These inclinations were selected empirically and useful images were difficult to achieve with angles much steeper than 40° or shallower than 25°.

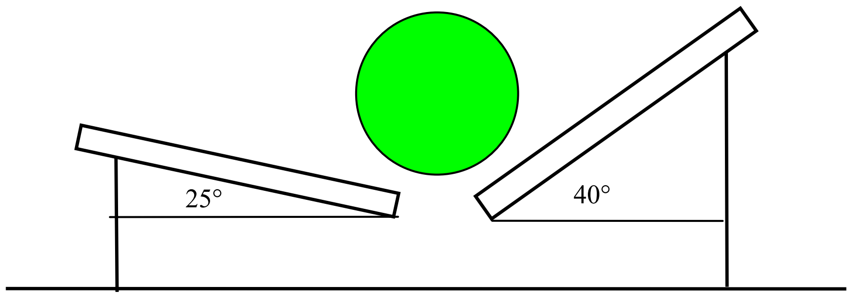


Figure 14. Mirror inclination diagram showing mirror positions at 25° and 40° from the horizontal.

Four conceptual mirror configurations are shown in Figure 15. Flat mirrors were not used because parabolic mirrors demonstrated better image resolution and less distortion. Also, only mirror configurations with an even number of mirrors were considered for two reasons: apples are bilaterally symmetric and the support wires effectively divide the imaging area into two bilaterally symmetric fields.

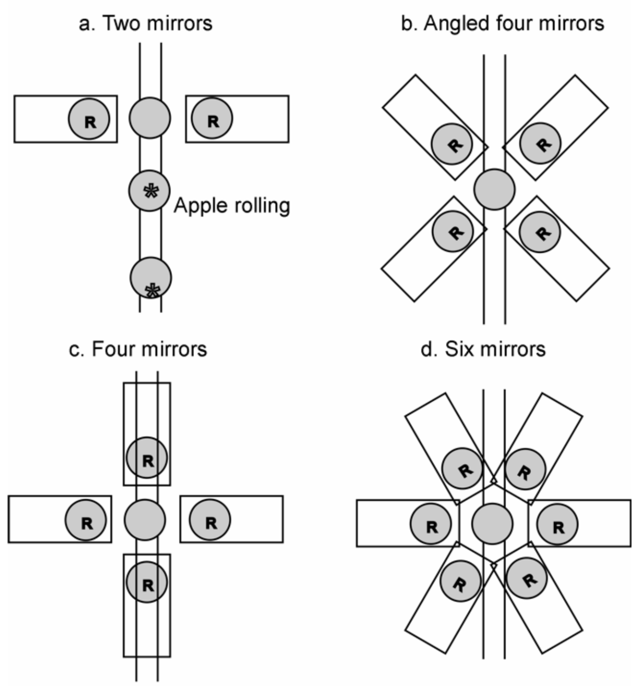


Figure 15. Schematic representations of using two, four, or six parabolic concave mirrors for image acquisition that show an apple supported by two wires surrounded by mirrors with reflected images of the apple. For the two mirror case, the effects of the apple rolling on the support wires is depicted to show that the visible portion of the apple changes over time.

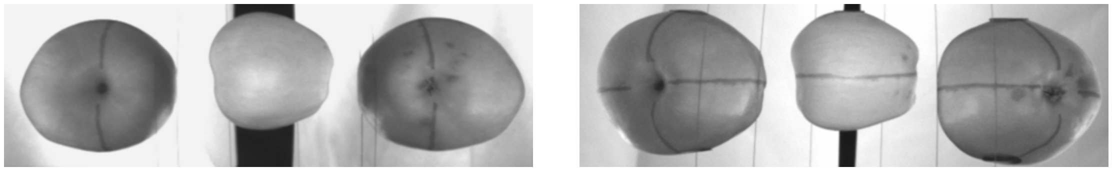
Data were analyzed by looking at sequences of images where one parameter was incremented. For presentation, the optimal and worst-case scenarios were selected. Worst-case was defined in terms of the difficulty of seeing inside the stem or calyx, or some area of the surface, in the set of images that equated to a single image using a particular mirror configuration. To allow visual assessment of the degree of a problem, the image with the problem area was depicted along with the surrounding incremented images. To facilitate localization of problem areas, lines were drawn on apples and round stickers were placed at critical locations.

For the angled four-mirror configuration, the worst case positioning of the stem/calyx axis is laterally 0° or 90° relative to the support wires. Most, if not all, apples are expected to be oriented with the stem/calyx axis perpendicular to the support wires. In addition, results will show that a 30° offset of the stem/calyx axis from the axis of paired-opposing mirrors can create problems for imaging inside the stem or calyx. The 30° angle is half the angle separating mirrors in the six-mirror configuration. A 45° offset for the angled four-mirror configuration would create even more of a problem. Since these two angles are the midpoints between mirrors in both configurations, they may be considered the most difficult scenarios to image and were chosen to test the any limitations of this imaging system.

Detection of nanogram quantities feces on apples is more difficult when the feces are at the edge of an apple surface in an image (Lefcourt et al., 2003). Thus, the optimal imaging configuration would produce sufficient imaging perspectives so that 100% of the surface could be analyzed without having to look near edges. Second, for safety inspection the goal is detection and not quantification. This goal allows consideration of configurations that cause shape distortions without requiring that the distortions be precisely mapped. Similarly, the existence of redundant information that might result from replicate sampling of some areas of the surface is not a problem. The only concern is that 100% of the surface is well represented.

Oriented Apple Imaging

Figure 16 depicts some perspectives that might be available for imaging an oriented apple using the two-mirror configuration.



a. b.

Figure 16. Typical images that would be acquired using the two-mirror configuration for an oriented apple. Dots on apple sides are barely visible. In a) mirror inclination is 40° while in b) mirror inclination is 25°.

The apple has large round stickers placed on the sides of the apples in the top and the bottom of theses images. These stickers are barely evident regardless of mirror inclination. Thus, while inclining the mirrors allows visualization of the bottom center of the apple, the areas with the stickers still do not appear in the acquired images and using just two mirrors is insufficient for imaging 100% of the surface. Two mirrors are inadequate to image whole surface in a single snapshot.

The mirror under wires image depicts the additional information that would be available if the four-mirror configuration was used (shown in Figure 17b below). The bottom of the apple and the sticker are clearly visible. An equivalent image of the other side of the apple would be possible from an opposite mirror, allowing for the whole surface to be imaged. For the four-mirror angled configuration, the image from one of the two mirror pairs is given in Figure 18. The other mirror pair for the four-mirror angled configuration would give equivalent imaging information (not shown).

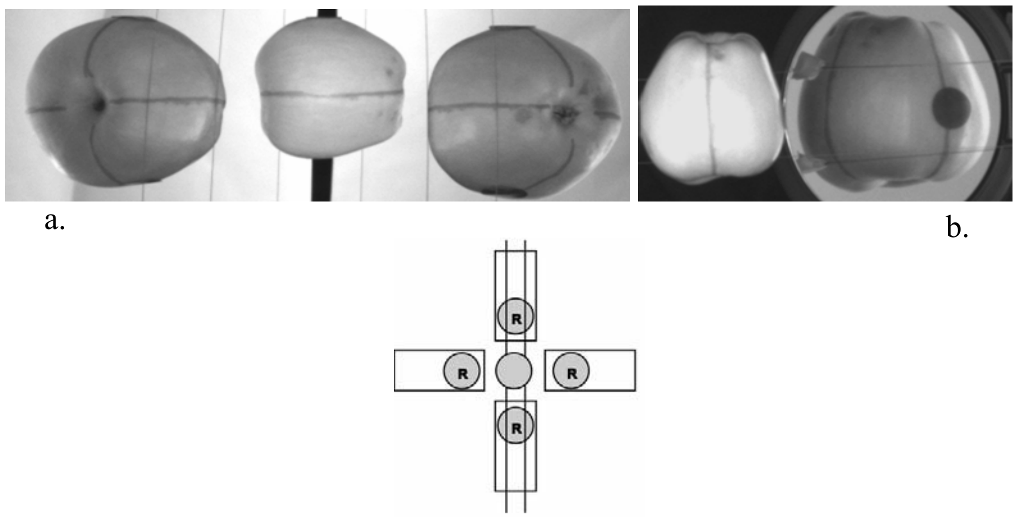


Figure 17. Original two mirror images are shown in 17a with the image from an additional mirror under the wires in the 4-mirror configuration in 17b. The opposing mirror under the wires would give equivalent information but reversed (not shown).

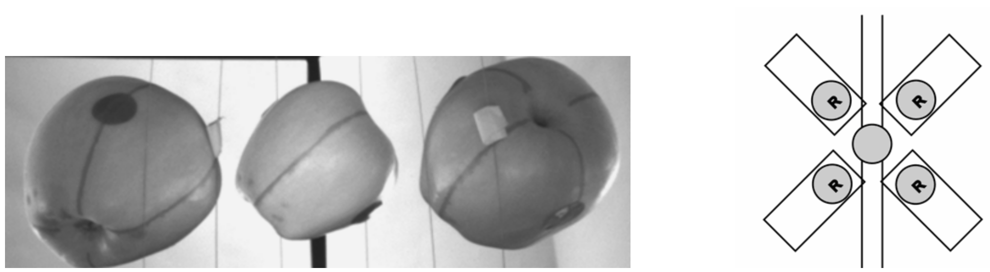


Figure 18. Images from one of the mirror pairs in the 4-mirror configuration (angled). The other mirror pair would give equivalent information but reversed (not shown).

The 60° images in Figure 19 (below) depict the additional information that would be available if a six-mirror configuration was used. The round stickers are clearly visible. While one edge the sticker for the 25° mirror inclination appears to be uncomfortably near the edge of the apple, the section of the sticker near the edge will be reversed in the -60° image (not depicted).

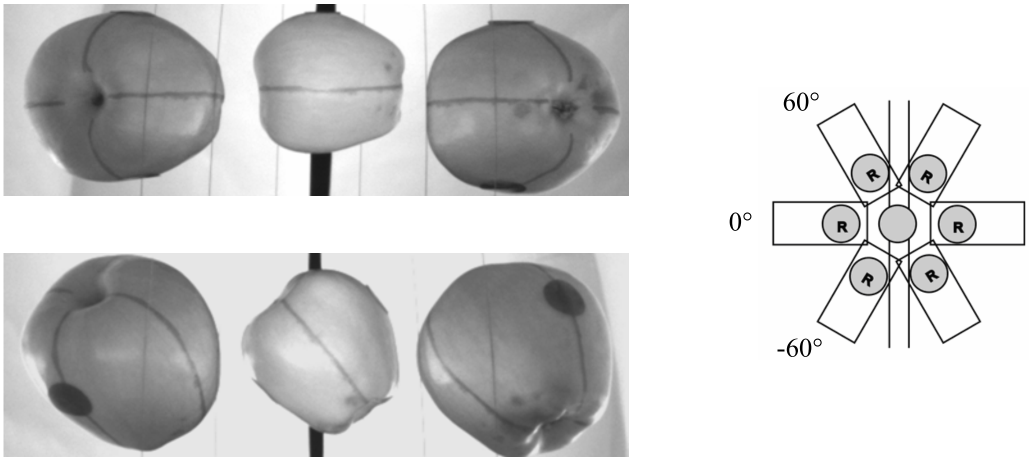


Figure 19. Images from the mirror pairs 0° and 60° in the 6-mirror configuration. The other -60° mirror pair would give equivalent information to the 60° but reversed (not shown).

Thus, both the four and six-mirror configurations are adequate to allow visualization 100% of an oriented apple's surface, minus the minuscule area obscured by the support wires. It should be noted that imaging using multiple angles (mirrors) reduces the already small interference of the support wires as only the points actually or nearly touching the apple are not imaged.

Oriented vs. Non-oriented Apple Imaging

Figures 20 and 21 depict the range of possible scenarios for imaging using the four-mirror configuration.

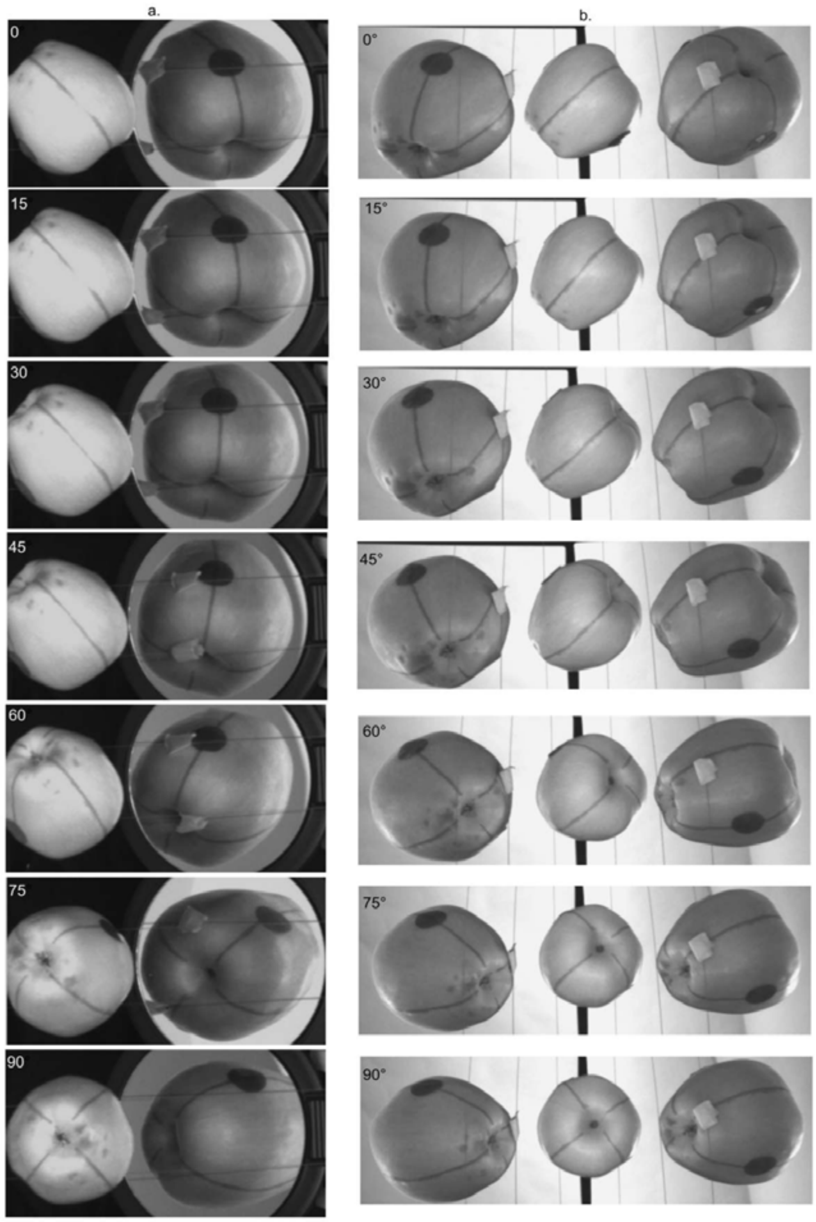


Figure 20. Non-oriented apple imaging, four-mirror configuration. Sequence of images using two mirrors at a higher (40°) angle of inclination along with perpendicular images from a mirror under the support wires. This represents the worst case scenario where the stem/calyx axis is laterally rotated 45° from the parallel support wires. The apple is rotated vertically from 0° to 90° at 15° increments.

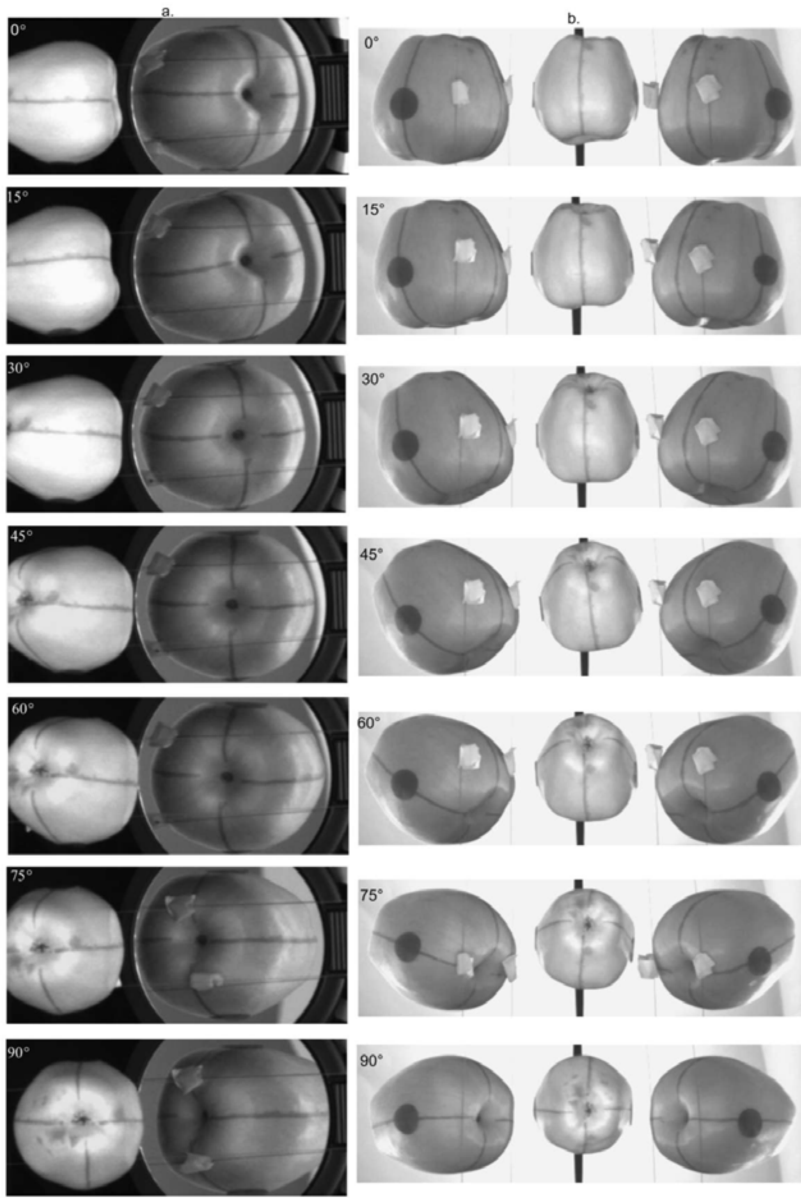


Figure 21. Non-oriented, perpendicular (upright) orientation apple imaging, four-mirror configuration. Sequence of images using two mirrors at a higher (40°) angle of inclination along with perpendicular images from a mirror under the support wires. The stem/calyx axis is laterally rotated 90° from the parallel support wires. The apple is rotated vertically from 0° to 90° at 15° increments.

There appears to be a small loss of information when the apple is laterally rotated 45° at the lower horizontal rotations. There also maybe some loss of information when the apple is laterally rotated 90° and horizontally rotated 45°. In general, the interior of the stem and calyx regions is less well represented than is the case for the six-mirror configuration (which will be shown).

Figures 22 and 23 depict a range of possible scenarios for imaging using the six-mirror configuration. One of the two most difficult imaging situations is when the apple is, or is approaching, upright (when the stem is most visible in the apple image). Under these conditions, the inside of the bottom stem or calyx is not completely rendered for the 40° mirror inclination. The other problem situation is when the apple is laterally rotated 30° and horizontally rotated 45°. In this case the problem is most evident with the 25° mirror inclination. Overall, the occurrence rate of imaging problems with randomly oriented apples should be low for both mirror inclinations and lowest for the 25° inclination since the latter provides better imaging of the bottom portion of the apple.

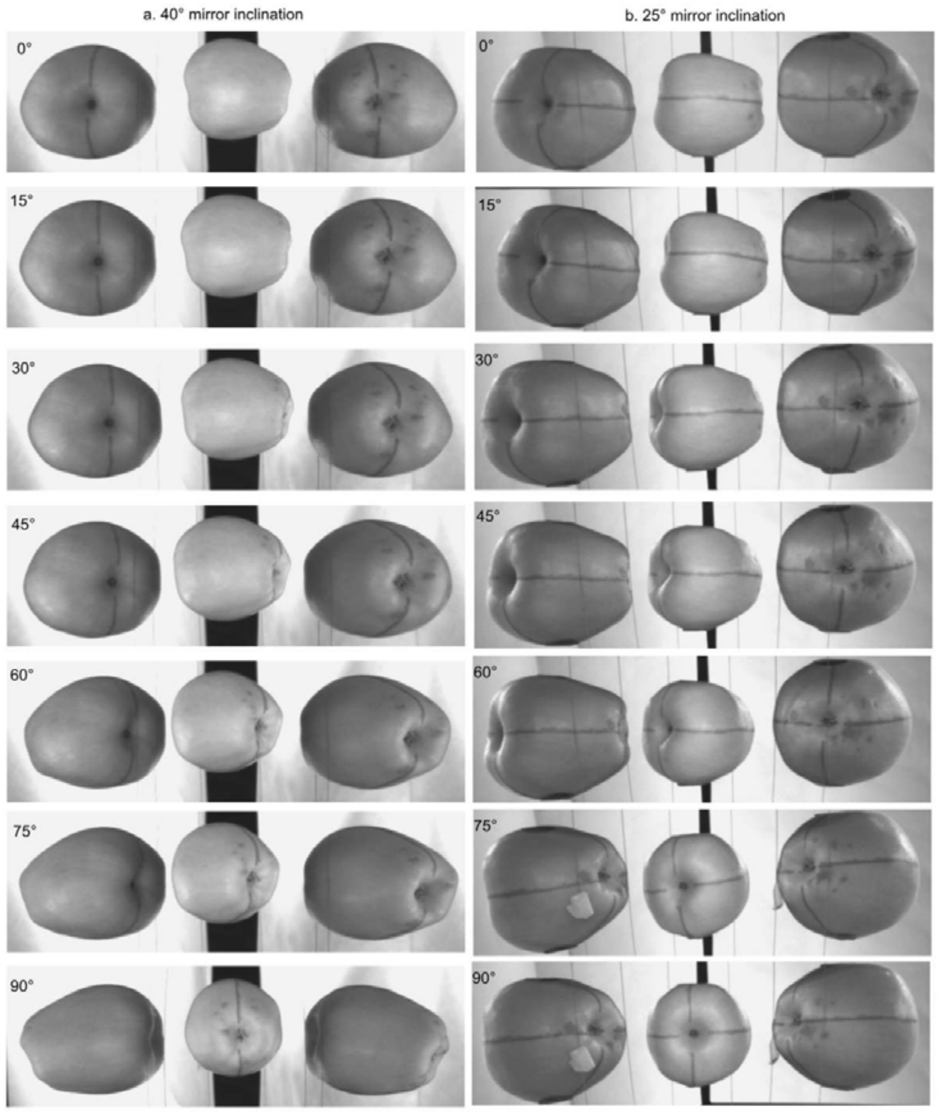


Figure 22. Non-oriented apple imaging, six-mirror configuration. Sequence of images using two mirrors at a higher (40°) and lower (25°) angle of inclination. The stem/calyx axis is perpendicular to the parallel support wires and the apple is rotated vertically from 0° to 90° at 15° increments. Note that with the 25° inclination the inside of the calyx is visible when the apple is fully vertical, but the stem is not visible with the 40° inclination.

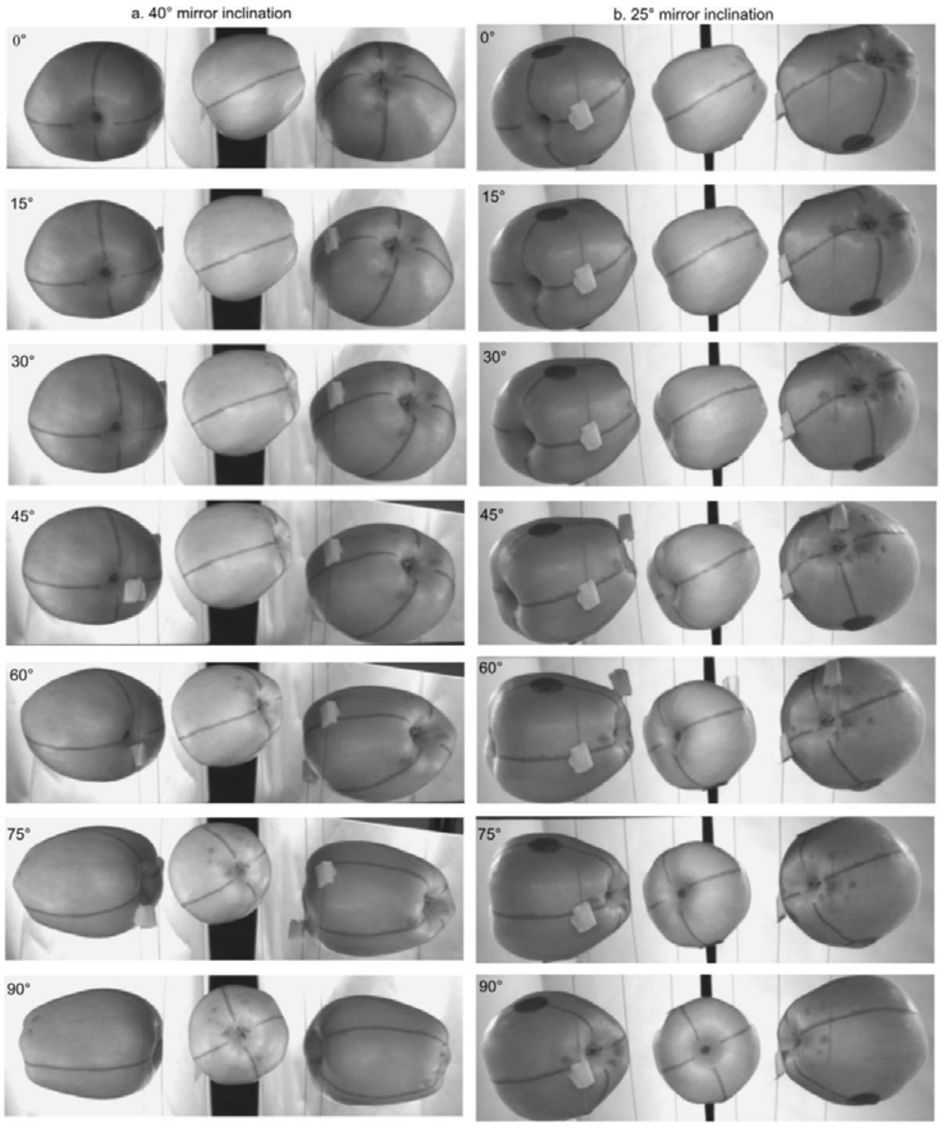


Figure 23. Non-oriented apple imaging, six-mirror configuration. Sequence of images using two mirrors at a higher (40°) and lower (25°) angle of inclination. The stem/calyx axis is laterally rotated 30° from the parallel support wires and the apple is rotated vertically from 0° to 90° at 15° increments. Note that for the 25° inclination a small amount of data about the inside of the calyx is lost at 45°.

Imaging Rolling Apples

There is an alternative to using a single image for detection. Multiple images could be acquired as the apple rolls through the imaging field as shown in Figure 24. This solution would not necessarily require additional images to be acquired, it would just be necessary to discern the location of an individual apple in a sequence of images given that the images might contain multiple apples. Imagining rate could be fixed or be a function of the location of apples on the track. However, multiple images per apple would be needed due to variable apple rotation rates and the randomness of presentation of the stem and calyx regions. One benefit of this imaging scheme is the elimination of the need for support wires. Apples could be imaged from above as the apples rolled down the orientation track. Figure 20 shows the information that might be acquired for an oriented apple using this imaging scheme.

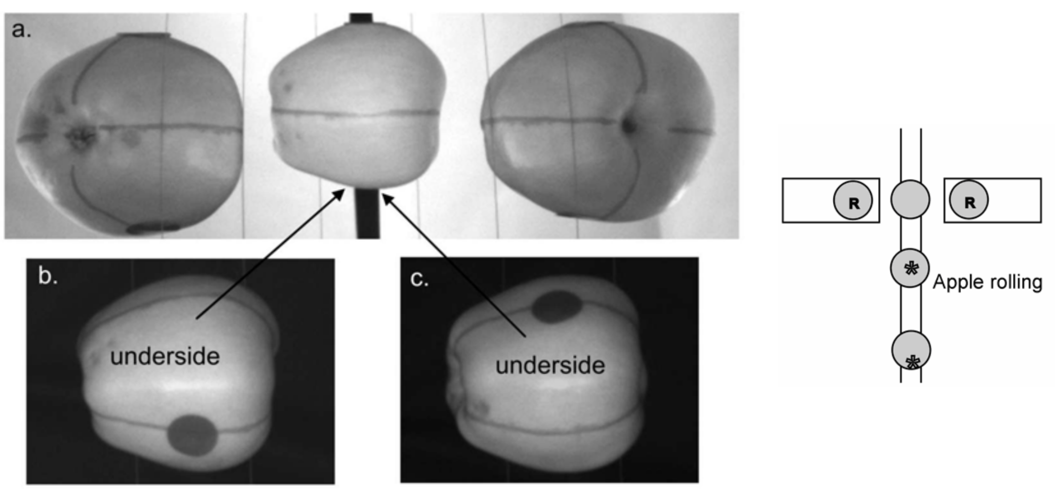


Figure 24. Information available using three sequential images as the apple rolls through the imaging area. The apple is in an oriented position.

Summary

Both the four- and six-mirror configurations were adequate to allow visualization of 100% of an oriented apple's surface. For non-oriented apples, *nearly* whole surface imaging was also possible using either the four- or six-mirror configuration; however, there were several positions where visualizing inside the stem or calyx area was difficult to achieve. The two-mirror configuration with multiple images as the apple rolled provided 100% visualization of both oriented and non-oriented apples. This information is summarized in Table 6.

Table 6. Summary of results from various mirror configurations.

	Mirror configuration	Whole surface	Comments
Oriented	2	No	Visualization of stem and calyx areas, but missing edge sections (see dot stickers on apple from Figure 24a)
Oriented	4	Yes	Visualization of stem and calyx areas AND visualization of edge sections
Oriented	6	Yes	Visualization of stem and calyx areas AND visualization of edge sections
Non-oriented	2	No	Visualization of stem and calyx areas, but missing edge sections
Non-oriented	4	Essentially	Visualization of stem and calyx areas for almost all orientations; for some can’t see 100% into stem/calyx
Non-oriented	6	Essentially	Visualization of stem and calyx areas for almost all orientations; for some can’t see 100% into stem/calyx
	2 (rolling)	Yes	Visualization of stem and calyx areas AND visualization of edge sections

No one configuration is the best option. There are pros and cons for all configurations and types. In comparing single versus multiple imaging, single images have less information to process but only one image is available. Multiple imaging has more images and data to process and initially it is the simplest to construct. For oriented apples, configurations using two, four (under wires and not angled) and six mirrors give the most direct view of the concave areas. A problem with the four-mirror configuration is that two of the mirrors are under the support wires. Images from these mirrors could be obstructed if apples were close together as they rolled through the imaging area. The four-mirror, angled configuration requires more complex analysis to determine the orientation of the apple. Four-mirror configurations have less equipment but the six-mirror configuration provides more data.

Considerations

Comparison to Existing Imaging Solutions

Currently, mirrors are not commonly used in commercial agricultural processing systems, primarily due to problems with dirt accumulation. Literature searches and online searches of commercial sorting systems failed to provide any evidence of use of parabolic concave mirrors in machine vision imaging system. The increased resolution and decreased distortion at the edges of images acquired using this type of mirror warrant consideration of their use.

The imaging method demonstrated by Li et al. (2002), which uses a cup holder with a hole in the bottom along with a camera below the cup and a camera above for imaging, faces major problems. The entire fruit cannot be imaged due to obstruction by the cup and the processing speed of 3 to 4 apples per second (which is slower than commercial speeds of 10 apples per second). Furthermore, their camera below the cup is just as likely as a mirror to get dirty, and the use of more than one camera diminishes the desirability of this system due to increased cost and complexity.

In addition, the system Li et al. (2002) propose assumes a vertical orientation of the apple's stem and calyx axis. But their experimental setup does not address a feeding or sorting system to ensure such orientation. If the apple stem-calyx axis is oriented in the cup at an angle less than 90º to the normal, the calyx region may not be visible to the camera. The system proposed in this project with music wire, a camera, and mirrors would be the end of an orientation and whole surface imaging system shown in Figure 25 below. The apples would roll off the wooden track proposed by Narayanan et al. (2007) onto the horizontal music wires where apples subsequently would be imaged.

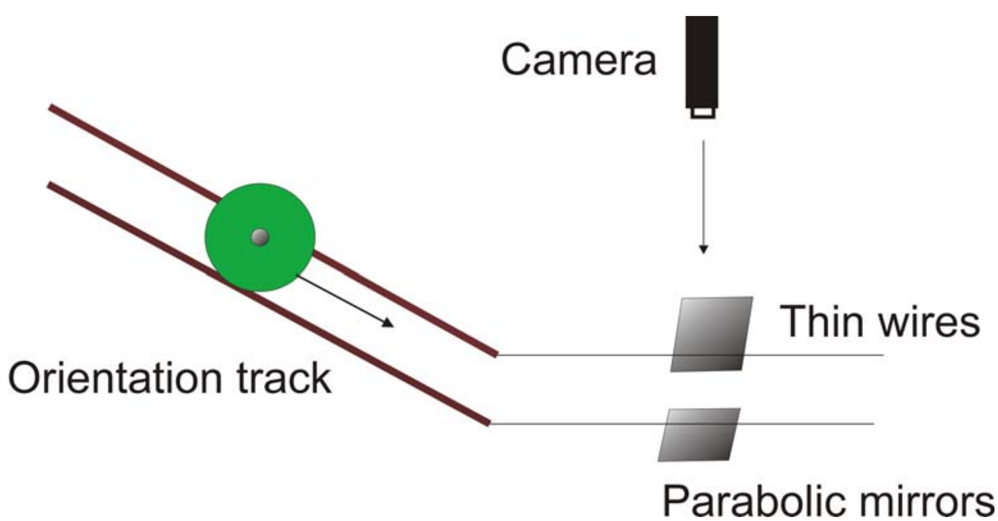


Figure 25. Schematic representation of a potential commercial apple processing system. The apple will be oriented so that the stem and the calyx regions face the parabolic concave mirrors used for imaging.

Feasibility

Fewer pieces of equipment simplify use and reduce maintenance costs. The two-mirror configuration has the least amount of equipment but is not sufficient to image 100% of the apple unless multiple images of a rolling apple are taken. The four-mirror configuration is preferred over the six-mirror configuration since it uses fewer mirrors while achieving similar ranges in imaging. Additionally, the six-mirror configuration would require smaller mirrors to fit in this system.

Economic feasibility must be considered with any imaging system design. Both initial and maintenance costs are important to industry. One camera and fewer mirrors help reduce cost and complexity. Camera and mirrors must also be protected from dust, dirt, apple bits, and water splash. A glass or plastic plate may be necessary to place between the imaging system and the apple conveyor to accomplish this.

Furthermore, economic labor costs should also be assessed. While a machine vision inspection system for removing defects may have a high initial capital cost, over time it may be a cost effective operation by saving on labor costs—especially as the price of labor rises. Presently, there are many unskilled laborers available. However, if this labor supply decreases, apple processors may favor further process mechanization.

Impact

Whole surface imaging provides an improvement in current automated quality inspection systems while adding the capability to detect for defects and contamination (food safety inspection). It has the potential to help prevent foodborne illness outbreaks associated with whole and fresh-cut apple produce by identifying fruit that is more susceptible to harboring pathogenic microorganisms. Other industries have been affected by foodborne illness outbreaks (such as pathogenic *E. coli)* and the negative public perception that has been associated with those products: the 2006 spinach outbreak cost California $74 million (AP, 2006) while last year's beef recall caused one of the country's largest ground beef manufacturers to go out of business (Belson & Fahim, 2006). The proposed whole surface imaging system from this project provides a novel technology for commercial apple inspection that is inexpensive and commercially applicable.

Chapter 6: Conclusion

Acquiring images representative of 100% of the surface of apples is difficult due to the concave nature of the stem and calyx regions. To test if mirrors could be used to image 100% of the surface of apples, configurations of two, four, and six mirrors were tested. Results demonstrated that single images acquired using the four- or six-mirror configurations, or a single image acquired using the two-mirror configuration along with multiple image acquisition as the apple rolled through the imaging field, could be used to image almost 100% of the surface of apples regardless of apple orientation. However, all configurations work best if the apples were oriented so that the stem region faced one mirror and the calyx region faced the opposing mirror. Parabolic concave mirrors with significant magnification improved image contrast and increased the resolution of acquired images compared to flat mirrors. These results suggest that consideration for using parabolic mirrors for commercial apple inspection is warranted.

Integrating this imaging system into a fruit orientation system would create a complete automated system capable of providing both quality and food safety inspection. This novel approach using parabolic mirrors also offers an improvement upon existing commercial imaging systems by providing an economical method for whole surface imaging since it uses minimal equipment and can be added to existing conveyor sorting systems.

Bibliography

Abadias, M., Usall, J., Oliveira, M., Alegre, I., and Vinas, I. 2008. Efficacy of neutral electrolyzed water (NEW) for reducing microbial contamination on minimally-processed vegetables. *Int. J. Food Microbiol.* 123(1-2): 151-158.

Abadias, M., Usall, J., Anguera, M., Solsona, C., and Vinas, I. 2008. Microbiological quality of fresh, minimally-processed fruit and vegetables, and sprouts from retail establishments. *Int. J. Food Microbiol.* 123(1-2): 121-129.

Achen, M. and Yousef, A.E. 2001. Efficacy of ozone against *Escherichia coli* O157:H7 on apples. *J.Food Sci.* 66(9):1380-1384.

Associated Press (AP). 2006. Winning back spinach eaters. MSNBC. Retrieved from www.msnbc.msn.com/id/15095551/ on March 14, 2008.

Aubrey, A. 2007. What does it take to clean fresh food? *Morning Edition*, NPR. September 20, 2007.

Belson, K. and K. Fahim. 2007. After extensive beef recall, Topps goes out of business. *New York Times.* Retrieved from www.nytimes.com/2007/10/06/us/06topps .html?_r=1&scp=1&sq=topps+beef+recall&st=nyt&oref=slogin on March 14, 2008.

Bennedsen, B.S. and Peterson, D.L. 2004. Identification of apple stem and calyx using unsupervised feature extraction. *Trans. ASABE* 47(3): 889-894.

Bennedsen, B.S., Peterson, D.L., and Tabb, A. 2005. Identifying defects in images of rotating apples. *Comput. Electron. Agr.* 48(2): 92-102.

Bennedsen, B.S. and Peterson, D.L. 2005. Performance of a system for apple surface defect identification in near-infrared images. *Biosyst. Eng.* 90(4): 419-431.

Beuchat, L.R. and Ryu, J. 1997. Produce handling and processing practices. *Emerg. Infect. Dis.* 3(4):459-465.

Bintsis, T., Litopoulou-Tzanetaki, E., and Robinson, R.K. 2000. Existing and potential applications of ultraviolet light in the food industry—a critical review. *J. Sci. Food Agric.* 80: 637-645.

Brosnan, T., and Sun, D.W. 2004. Improving quality inspection of food products by computer vision - a review. *J. Food Engin.* 61(1): 3-16.

Campins, J., Throop, J.A., and Aneshansley, D.J. 1997. Apple stem and calyx identification for automatic sorting. ASAE Paper No. 97-3079. St. Joseph, Mich.:ASAE.

Centers for Disease Control and Prevention. 1996. Outbreak of *Escherichia coli* O157:H7 infections associated with drinking unpasteurized commercial apple juice—British Columbia, California, Colorado, and Washington, October 1996. *MMWR* 45(44): 975.

Centers for Disease Control and Prevention. 1997. Outbreaks of Escherichia coli O157:H7 Infection Associated with Eating Alfalfa Sprouts -- Michigan and Virginia, June-July 1997. *MMWR* 46(32): 741-744.

Centers for Disease Control and Prevention. 1999. Outbreak of *Salmonella* serotype Muenchen infections associated with unpasteurized orange juice—United States and Canada, June 1999. *MMWR* 48: 582-585.

Centers for Disease Control and Prevention. 2002. Multistate outbreaks of *Salmonella* serotype Poona infections associated with eating cantaloupe from Mexico—United States and Canada, 2000-2002. *MMWR* 51(46): 1044-1047.

Centers for Disease Control and Prevention. 2006. Ongoing Multistate Outbreak of Escherichia coli serotype O157:H7 Infections Associated with Consumption of Fresh Spinach—United States, September 2006. *MMWR* 55(38): 1045-1046.

Centers for Disease Control and Prevention. 2007. *Salmonella* Oranienburg infections associated with fruit salad served in health-care facilities—northeastern United States and Canada, 2006. *MMWR* 56(39): 1025-1028.

Chen, Y.R., Chao, K., and Kim, M.S. 2002. Machine vision technology for agricultural applications. *Comput. Electron. Agr.* 33(2/3): 173-191.

Compac Company Website. 2007. Retrieved from http://www.compacsort.com/wa.asp?idWebPage=14833&idDetails=105 on June 12, 2007.

Corkidi, G., Balderas-Ruíz, A., Taboada, B., Serrano-Carreón, L., Galindo, E. 2006. Assessing mango anthracnose using a new three-dimensional image-analysis technique to quantify lesions on fruit. *Plant Pathol.* 55: 250-257.

Cummings, K., Barrett, E., Mohle-Boetani, J.C., Brooks, J.T., Farrar, J., Hunt, T., Fiore, A., Komatsu, K., Werner, S.B., and Slutsker, L. 2001. A multistate outbreak of *Salmonella enterica* serotype Baildon associated with domestic raw tomatoes. *Emerg. Infect. Dis.* 7(6): 1046-1048.

Fatemi, P., LaBorde, L.F., Patton, J.,Sapers, G.M., Annous, B., and Knabel, S.J. 2006. Influence of punctures, cuts, and surface morphologies of golden delicious apples on penetration and growth of *Escherichia coli* O157:H7. *J. Food Prot.* 69(2): 267-275.

Feng, P. and Weagant, S.D. 2002. Bacteriological Analytical Manual Online. Diarrheagenic *Escherichia coli*. Retrieved from http://www.cfsan.fda.gov/~ebam/bam-4a.html on June 5, 2007.

Fresh Cut. 2006. Fresh cut trends. 2006. Retrieved from http://www.freshcut.com/pages/arts.php?ns=438 on October 11, 2007.

Hecht, E. 1998. *Optics.* Addison-Wesley Longman, Inc., Reading, PA, 177-189.

Hilborn, E.D., Mshar, P.A., Fiorentino, T.R., Dembek, Z.F., Barrett, T.J., Howard, R.T., and Cartter, M.L. 2000. An outbreak of *Escherichia coli* O157:H7 infections and haemolytic uraemic syndrome associated with consumption of unpasteurized apple cider. *Epidemiol. Infect.* 124: 31-36.

Imou, K., Kaizu, Y., Morita, M., and Yokoyama, S. 2006. Three-dimensional shape measurement of strawberries by volume intersection method. *Trans. ASABE.* 49(2): 449-456.

Jay, J.M., Loessner, M.J., and Golden, D.A. 2005. *Modern Food Microbiology, 7th Ed.* Springer, New York, 625, 628, 645.

Kim, M.S., Lefcourt, A.M., Chen, Y.R, Kim, I., Chan, D.E., and Chao, K. 2002. Multispectral detection of fecal contamination on apples based on hyperspectral imagery: Part II. Application of hyperspectral fluorescence imaging. *Trans. ASAE* 45(6): 2039-2047.

Kudva, I.T., Blanch, K., and Hovde, C. 1998. Analysis of *Escherichia coli* O157:H7 survival in ovine and bovine manure and manure slurry. *Appl. Environ. Microb.* 64(9): 3166-3174.

Lakakul, R., Beaudry, R.M., and Hernandez, R.J. 1999. Modeling respiration of apple slices in modified-atmospheric packages. *J. Food Sci.* 64: 105-110.

Lal Kaushal, B.B and Sharma, P.C. 1995. *Fruit Science and Technology* (Salunkhe, D.K. and Kadam, S.S., eds.) Marcel Dekker, Inc., New York, 91-112.

Leemans, V., Magein, H., and Destain, M.F. 2002. On-line fruit grading according to their external quality using machine vision. *Biosyst. Eng.* 83(4): 397-404.

Lefcourt, A.M., Kim, M.S., Chen, Y.R. 2003. Automated detection of fecal contamination of apples by multispectral laser-induced fluorescence imaging. *Appl. Optics* 42(19): 3935-3943.

Lefcourt, A.M., Kim, M.S., Chen, Y.R. 2005. Detection of fecal contamination on apples with nanosecond-scale time-resolved imaging of laser-induced fluorescence. *Appl. Optics* 44(7): 1160-1170.

Li, Q., Wang, M., and Gu, W. 2002. Computer vision based system for apple surface defect detection. *Comput. Electron. Agr.* 36(2-3): 215-223.

Lu, J.Y., Stevens, C., Khan, V.A., and Kabwe, M. 1991. The effect of ultraviolet irradiation on shelf-life and ripening of peaches and apples. *J. Food Quality*. 14: 299-305.

Martinez-Ferrer, M., Harper, C., Perez-Munoz, F., and Chaparro, M. 2002. Modified atmospheric packaging of minimally processed mango and pineapple fruits. *J. Food Sci*. 67(9): 3365-3371.

Mead, P.S., Slutsker, L., Dietz, V., McCaig, L.F., Bresee, J.S., Shapiro, C., Griffin, P.M., and Tauxe, R.V. 1999. Food-related illness and death in the United States. *Emerg. Infect. Dis*. 5: 607-625.

Mendonca, A. 2005. *Produce Degradation: Pathways and Prevention*. (Lamikanra, O., Imam, S.H., and Ukuku, D., eds.) Taylor & Francis, Boca Raton, LA, 441-453.

Murano, P.S. 2003. *Understanding Food Science and Technology*. Wadsworth/Thomson, Belmont, CA, 241-247.

Narayanan, P.,Lefcourt, A.M., Tasch, U., Rostamian, R., Grinblat, A., and Kim, M.S. Theoretical aspects of orienting fruit using stability properties during rotation. ASAE Meeting Presentation. Portland, Oregon. Paper No.: 061144, 2006.

Parish, M.E., Beuchat, L.R., Suslow, T.V., Harris, L.J., Garrett, E.H., Farber, J.N., and Busta, F.F. 2003. Methods to reduce/eliminate pathogens from fresh and fresh-cut produce. *Compr. Rev. Food Sci. F.* 2 (Supplement): 161-173.

Peterson, D.L., Bennedsen, B.S., Anger, W.C., and Wolford, S.D. 1999. A systems approach to robotic bulk harvesting of apples. *Trans. ASABE*. 42(4): 871-876.

Reed, A.N. 2003. *Concise Encyclopedia of Temperate Tree Fruit (*Baugher, T.A. and Singa, S., eds.) Haworth Press, Inc., New York, 209-217 and 309-316.

Sapers, G.M. 2001. Efficacy of washing and sanitizing methods for disinfection of fresh fruit and vegetable products. *Food Technol. Biotechnol.* 39(4):305-311.

Serway, R.A. and Beichner, R.J. 2000. *Physics for Scientists and Engineers with Modern Physics*, Vol. 2. Saunders College Publishing, Fort Worth, Texas, 1140-1149.

Sivapalasignam, S., Friedman, C.R., Cohen, L., and Tauxe, R.V. 2004. Fresh produce: a growing cause of outbreaks of foodborne illness in the United States, 1973 through 1997. *J. Food Prot.* 67(10): 2342-2353.

Thayer, D.W. and Rajkowski, K.T. 1999. Developments in irradiation of fresh fruits and vegetables. *Food Technol*. 53(11): 62-65.

Throop., J.A., Aneshansley, D.J., Upchurch, B.L., and Anger, B. 2001. Apple orientation on two conveyors: performance and predictability based on fruit shape characteristics. *Trans. ASABE*. 44(1): 99-109.

Tipler, P.A. 1999. *Physics for Scientists and Engineers.* W.H. Freeman and Co., New York, 1070-1074.

U.S. Dept. of Agriculture, Agricultural Marketing Service. 2002. United States standards for grades of apples. USDA. Retrieved from www.ams.usda.gov/standards/apples.pdf on October 4, 2007.

U.S. Dept. of Agriculture, Economic Research Service. 2005. *Fruit and Tree Nuts Outlook.* FTS-315.

U.S. Dept. of Agriculture, National Agriculture Statistics Service. 2007. *Noncitrus fruits & nuts 2006 summary.* USDA. Retrieved from http://usda.mannlib.cornell.edu/ usda/current/NoncFruiNu/NoncFruiNu-07-06-2007.pdf on October 11, 2007.

U.S. Food and Drug Administration. 1999. Report of 1997 inspections of fresh, unpasteurized apple cider manufacturers. FDA-CFSAN. Retrieved from http://www.cfsan.fda.gov/~dms/ciderrpt.html on November 8, 2006.

U.S. Food and Drug Administration. 1999. Investigators' Reports: Juice maker fined record amount for E. coli contaminated product. FDA. Retrieved from www.fda.gov/fdac/departs/1999/199_irs.html on March 15, 2008.

U.S. Food and Drug Administration. 1999. FDA issues nationwide health warning about Sun Orchard unpasteurized orange juice brand products. FDA. Retrieved from http://www.fda.gov/bbs/topics/NEWS/NEW00685.html on February 17, 2008.

U.S. Food and Drug Administration. 2001. *Food Safety A to Z Reference Guide*. FDA-CFSAN. Retrieved from http://www.cfsan.fda.gov/%7Edms/a2z-e.html on June 5, 2007.

U.S. Food and Drug Administration. 2006. *Bad Bug Book.* FDA-CFSAN. Retrieved from http://www.cfsan.fda.gov/~mow/chap15.html on June 5, 2007.

U.S. Food and Drug Administration. 2007. Recall--Dole Fresh Vegetables announces voluntary recall of 'Dole Hearts Delight' packaged salads. FDA. Retrieved from http://www.fda.gov/oc/po/firmrecalls/dole09_07.html on February 29, 2008.

U.S. Food and Drug Administration. 2007. FDA finalizes report on 2006 spinach outbreak. FDA. Retrieved from http:www.fda.gov/bbs/topics/NEWS/2007/ NEW01593.html on March 15, 2008.

Vargas, A.M., Kim, M.S., Tao, Y, and Lefcourt, A.M. 2005. Detection of fecal contamination on cantaloupes using hyerspectral fluorescence imagery. *J. Food Sci.* 70(8): 471-476.

Wen, Z. and Tao, Y. 2000. Dual-camera NIR/MIR imaging for stem-end/calyx identification in apple defect sorting. *Trans. ASAE* 43(2): 449-452.

Wireman, G.B., Granatstein, D., Kirby, E., Adams, E, and Ingham, S. 2001. Reducing food safety risks in apples—a self-assessment workbook for producers of apples, juice, and cider. Cooperative Extension, Washington State University. Retrieved from http://organic.tfrec.wsu.edu/FoodSafetyWeb/Self%20Assessment.pdf on February 15, 2008.

Xu, L. 1999. Use of ozone to improve the safety of fresh fruits and vegetables. *Food Technol.*. 53(10): 58-63.

Yang, Q. 1992. The potential for applying machine vision to defect detection in fruit and vegetable grading. *Agr. Eng.* 47(3): 74-79.