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Sorting Carrots with Machine Vision

S.W. Searcy, U.M. Peiper, R. Feller

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Bet Dagan, ISRAEL

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Title

Sorting Carrots with Machine Vision

Investigator's Names

Stephen W. Searcy

Uri M. Peiper

Ron Feller

Investigator's Institutions

Texas A&M University

A.R.O., The Volcani Center

A.R.O., The Volcani Center

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Signatures

Principal Investigator

Stephen W. Searcy
Stephen W. Searcy

Institution's Authorizing Official

Fred B. Mesler

Fred B. Mesler

Manager

Contracts and Grants Division

Texas A&M Research Foundation

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Abstract

Investigations were undertaken to develop methodologies for handling and grading fresh market carrots at commercially acceptable rates. Initial plans were to use a ring configuration of fiber optics as the sensing device. Simulations of the fiber optic ring showed that a circular configuration would not allow detection of size and shape parameters for the individual carrots, and would also be sensitive to the misalignment in the sensing area. The same simulation showed that a three or four sided sensing array would be most appropriate. As a result, the vision investigations were concentrated on a sensing system concept consisting of three line scan cameras located at 120° angles. Spectrophotometer measurements were made to characterize the reflective properties of normal carrot flesh and various defects. Image processing algorithms were developed to analyze carrot size, shape defects and surface defects. The results of those algorithms were used to classify carrots as normal or cull. Classification was done using conventional statistical techniques and neural networks. Results showed that neural networks are superior to statistical classifiers, reducing the classification errors from a typical value of 12% to less than 5%. The carrot handling system was designed to singulate carrots and pass them axially through the sensing area.

Original Objectives

1. Develop methods of three dimensional inspection of carrots for defects and size at 5-10 carrots per second, including imaging equipment, lighting techniques and processing methods.
2. Develop handling equipment which can singulate carrots and present them in a manner suitable for full surface inspection at rates of 5-10 carrots per second.

Report of Research

Introduction

The purpose of this research was to develop algorithms and mechanisms that would form the basis for a commercially viable carrot grading system. This involved investigations into both the sensing and handling aspects of the problem. In the original proposal, a sensing element consisting of a circular ring of optical fibers was suggested. Work in Texas concentrated initially on increasing the knowledge of carrot defects and their characteristics. Later efforts were devoted to the development of image processing and classification algorithms. At the same time, a simulation of the fiber optic sensor was made in Israel. The design, construction and testing of the carrot handling mechanisms was also performed by Israeli cooperators. The following sections describe the work performed and the results obtained in each of these areas. Since details of most of the work have been described in several technical publications, these are included in the appendices. The information provided below is a summary of the methods and results for each component of the investigation.

Simulation of the Fiber Optic Sensor

An innovative sensor was conceived to serve as the sensing element of the carrot inspection system. This sensor was to consist of an array of optical fibers attached to a line scan camera such that each fiber gathered the light for a single pixel. In this configuration, each fiber could gather light reflected normal to the carrot surface (Figure 1). However, the optimum configuration of the fibers was unknown. A simulation was performed to evaluate various fiber configurations and carrot positions within the sensing ring. A complete description of the work is given in the paper entitled *A Simulation of Sorting Carrots by Machine Vision* by Uri. M. Peiper and F. Geoola (Appendix A).

The objective of the simulation study was to identify the optimum configuration of fibers which would provide information on the size and shape of carrots, as well as information about surface blemishes. Included in the simulation analysis were the following variables.

Figure 1. A conceptual drawing of the proposed fiber optic sensor with an off-center carrot.

1. the shape of the sensor
2. the spacing between optical fibers
3. the number of optical fibers in the sensor
4. carrot diameter
5. carrot position relative to the center of the sensor.

The shapes considered had 2, 3, 4, 5, 6, and 12 sides plus circular. The spacing and number of fibers were functions of the sensor shape. Two carrots diameters of 10 and 30 mm were used to represent small and large carrots respectively. The simulated carrots were placed in two positions, the sensor centerline and 20 mm from the centerline. Each configuration was analyzed to determine it's ability to measure the carrot diameter and the portion of the surface viewed. The surface viewing was considered in two ways, the amount of the surface that was not viewed by any fiber, and the amount of surface that was viewed by multiple fibers. In addition, a distortion measure was included. Distortion was defined as the real length of the surface viewed by a fiber to the fiber diameter.

Results of the simulation indicated that only square, triangular or parallel configurations are appropriate for sensing the carrot quality. All other configurations showed significant sensitivity to the carrot location relative to the centerline. Since the carrot travel path can not be accurately controlled by the handling equipment, insensitivity to position was important.

Based on the results of the simulation, implementation of the fiber optic sensor was dropped. The primary reason for using the fiber optics was to allow viewing angles not possible with cameras. After the simulation results indicated that linear arrays gave the best performance, there was no reason to include the expense of fiber optics. Development of the sensing system was oriented toward the use of three line scan camera equally spaced around the carrot travel path. Figure 2 shows the sensing concept used in the remainder of the project.

Carrot Reflectance Measurements

At the time of this research, no published data were available to describe the spectral reflectance properties of normal and defective carrots. Since spectral information is highly useful in detecting various types of defects, an investigation of the light reflectance from normal carrot flesh and blemished carrot flesh was performed. The types of defects tested

Figure 2. The design of a line scan sensing system for three dimensional examination of carrots.

were dry rot, soft rot, black crown, and cavity spots. This information, combined with the spectral characteristics of other optical elements in the sensing system, was used to optimize the maximum contrast between normal and defective carrots.

In cooperation with the USDA-ARS R. B. Russell Research Center, Athens, GA, carrot body reflectance was measured with an integrating spectrophotometer over the wavelengths 486 to 1043 nm. Characteristic curves consisting of mean and 95% confidence intervals were constructed. A typical graph comparing the results of normal and dry rot carrot tissue is illustrated in Figure 3.

Between 535 and 722 nm wavelengths, the reflectance intensities of three of the four defects were statistically different from that of the normal carrot flesh. Cavity spots did show a difference, although it was not statistically significant. The instrument used in this investigation was unable to focus only on the small cavity spots. Consequently, a portion of the normal flesh was included in these measures.

Figure 3. A comparison of sound carrots and carrots with dry rot using 95% prediction confidence intervals.

Based on the spectral information, a bandpass filter centered at 655 nm with a 70 nm passband was chosen to be used with the machine vision inspection system. In addition to the interference filter, an illumination hood was constructed to facilitate diffuse lighting conditions. The hood was mounted over a conveyor belt. The combination of the

illumination hood and interference filter provide near optimal illumination for the inspection system. This arrangement was used for all subsequent vision work.

This research is more fully described in the publication entitled *Reflectance Characteristics of Fresh-Market Carrots* by Howarth, Searcy and Birth (Appendix B).

Defect Detection Algorithms

Feature extraction techniques were developed to characterize the difference between normal and cull carrots. The three characteristics which define this difference are size, shape, and surface abnormalities. The types of defects which were understood to be the most common and critical and to be detectable using machine vision are size (length and diameter), shape (crooked, broken, forked, and root constriction) and surface (cavity spots, dry rot, soft rot, and black crown).

In order to obtain maximum processing speed, binary imaging techniques were used. The use of optical filtering and thresholding provided adequate images. The first technique employed to extract edges in the image was run length encoding (RLE). In the binary images, the edges provided information about the carrot outline and any internal features. This method was chosen over chain coding because RLE was more suited for use with line scan cameras. The chain coding algorithm requires digitization of a full image before further processing is implemented. RLE can be activated following digitization of each line; therefore, additional processing can also be carried out. Using RLE, other feature extraction methods were developed. Measurement of length and diameter was simple. Maximum carrot diameter was the maximum difference between first and last transitions and carrot length was difference between the first and last rows. More complex algorithms were needed to characterize the other defects.

The curvature features were developed based on an extraction procedure presented by Levine (1985). This extraction procedure is an approximation of the second derivative of the carrot centroid profile (ASD). A demonstration of the procedure is illustrated in Figure 4 for a crooked carrot. Using the ASD profile, three features were extracted: average and maximum values of the curvature profile and the number of values above a threshold. These values were able to characterize the various curves that could be expected.

The feature extraction methods developed to characterize broken and root constricted carrots were based on the first derivative of the diameter profile (FDP). In Figures 5a and 5b, the diameter profile and FDP are shown comparing normal and broken carrots respectively. From this information, three features were extracted: the average value of the FDP, the first difference of the FDP for a window around the carrot tip, and distance from the crown to maximum width. These features were capable of characterizing both broken crowns and broken tips.

Figure 4 Example of calculation of ASD profile for a crooked carrot.

To identify forking and surface defect regions, a modified version of the connected components algorithm (Ronse and Devijver, 1984) was developed. This technique divides a binary image into blocks and defines the connected relationships between blocks. An example of a forked carrot with a surface defect is shown in Figure 6. Surface defects are surrounded by connecting blocks. Fork regions can be described as a convex hull and are separated from the connected body by a hinge block. The number of occurrences of each defect type and the associated defect area are extracted using the relational information.

More detailed information on the image processing algorithms is available in the paper entitled *Algorithms for Grading Carrots by Machine Vision* by Howarth and Searcy (Appendix C).

Figure 5a. Example diameter profile and it's first derivative (FDP) for a normal carrot.

Figure 5b. Example diameter profile and it's first derivative (FDP) for a broken carrot.

Figure 6. Illustration of modified connected components algorithm on a carrot with a surface defect and fork.

Classification of Cull and Normal Carrots

Using the feature extraction methods described above, a comprehensive decision model was developed to classify carrots as acceptable or cull and is shown in Figure 7. A statistical classifier, the Bayes decision rule, was first used. Using the two-category classification case, decision functions were constructed for each appropriate carrot characteristic.

Size Measurement: The vision system was first calibrated by imaging five circular metallic disks. Calibration curves were developed and size limits were calculated for carrot length and diameter measurement. Size limits were set as 127 to 203mm for length sizing and 19 to 40mm for diameter. These values were consistent with both USDA grade and industry quality standards. Type I and II errors were 10.7% and 20.2%, respectively. Since the limits chosen for determining size defects were not identical to those used by manual graders, these errors are not a true indication of the accuracy of the vision system. They primarily indicate inaccuracies of the manual and mechanical grading processes. Based on the 0.5 mm resolution of the vision system, it was judged that size measurements would contribute no more than 2 percent total misclassification.

Curvature: The early testing used only the average ASD value. A two-category univariate Bayes decision model was developed. Out of 98 carrots tested, the Type I and II errors were 2.0% and 13.3% respectively, for a total misclassification rate of 15.3%. After further testing, two additional features were added to increase the dimensionality. A multivariate

Figure 7. Decision model for carrot classification. A feature vector, $\mathbf{x}_i$, is input and the resulting class is output, acceptable or cull.

Bayes model was developed and the total misclassification rate was reduced to 3.2% in the training set of carrots, and 2.9% in the validation set. Both misclassification rates were identical for Bayes classifiers developed with normal and log-normal distributions. The use of a Counter Propagation neural network resulted in 4.4% total misclassification.

Brokenness: In initial testing, a single feature, the average FDP, was used for classification. As with the curvature decision model, a two-category univariate Bayes model was developed. After classifying 150 normal and broken carrots, the Type I and II errors were 4.7% and 2.7% respectively, with a total misclassification rate of 7.3%. This test set of carrots was limited, however, in that it only contained carrots with broken tips. It was realized that the recognition of broken crowns would require new features. After adding the first difference of the FDP and the crown to maximum diameter feature, further testing was performed. The misclassification for brokenness increased from 7.3% to 17.3% when broken crown carrots were included and a log-normal classifier was used. A Counter Propagation neural network decreased the total misclassification to 9.9% for the same set of carrots.

Forking: The decision criteria for classifying forked carrots was the identification of a sufficiently large region that was forked. Only 1 normal carrot out of 81 was misclassified, giving a total misclassification rate was 1.2%. Due to the low number of forked carrots in the sample population, this low misclassification rate may be overly optimistic. There are special cases which exist that declare normal carrots to be cull. Boundary edge noise is an example. The convex hull area of the carrot is also computed by the connected components algorithm. With this measure and the fork position, it is likely that misclassification due to

special cases can be reduced.

Surface Defects: The modified connected components algorithm identifies surface defects and computes the associated areas. A two-category univariate Bayes model was developed for determining the acceptable total defect area. From a total of 81 carrots, Type I and II errors were both 2.5%, for a total misclassification rate of 5.0%. Of the entire sample population, only six were blemished carrots. Therefore, the significance of the low misclassification rate should be guarded.

Overall: The overall classification results revealed that neural networks can be used to reduce the total misclassification rate to less than 5%, as compared to approximately 12% for statistical classifiers. These values are determined by considering the percentages of both defect and normal carrots, and the Type I and II errors.

For the decision function using a Bayes model, it was assumed that the features were normally distributed. This was determined to be false for some features. Since the Bayes rule assumes that a probability distribution function is known, non-normality of the features was identified as a possible source of the remaining classification error. In view of these limitations, alternative classification methods were investigated.

Neural networks do not assume that a probability distribution function is known; therefore, several network topologies were investigated. Of the neural networks explored, the most promising was the functional link backpropagation network. The misclassification rate was reduced to 4.4% for curvature and 9.9% for brokenness.

Although this project has expired, work on classification and grading continues. Most of the work described here was performed by M. Scott Howarth, at doctoral student in Agricultural Engineering. He is doing this work for his dissertation. In order to complete his dissertation, Mr. Howarth will integrate the classifiers for each feature into a complete grading system.

This research is described in more detail in SPIE Proceedings Vol. 1379:141-150 and ASAE Paper No. 91-7012 (Appendices D, E).

Carrot Handling Equipment

A mechanical device capable of transferring carrots in batches from a bulk bin, singulating them, and feeding them through a sensing zone was built and laboratory tested. The sensing zone was represented by a ring with an internal diameter of 60 mm.

The carrot singulator was constructed of two main subsystems.

1. A vibratory feeder which receives the carrots from the bulk bin by a bucket conveyor and discharges them into a V-shaped channel. This feeder receives the carrots in batches, spreads them on its own surface and orients them in one direction while moving them

toward the discharge channel. From this channel, the carrots are dropped some 10 cm on the cylinder singulator.

2. The cylinder singulator consisted of two pairs of inclined, polished, stainless steel counter-rotating cylinders. The lower pair had a 5 mm gap between the rollers and did not permit any carrots to fall through. The upper pair had a large gap and permits all carrots to fall through onto the lower pair. All rollers rotated outward from the channel. The carrots accelerated along the cylinders, due to the moisture of the contact surfaces, the low friction of the rollers and the inclination. The linear uninterrupted movement of the carrots at the end of the lower rollers allowed for a free fall of the carrots on a parabolic trajectory through the ring which simulated the sensor.

The experimental singulator allowed for maximal flexibility. All parameters like the frequency and inclination of the feeder, the rotational speed of the rollers and their inclination etc., were all easily adjusted in order to get optimal performance. Preliminary tests showed good performance of the singulator.

Very few carrots showed "double feeding" of two carrots attempting to enter the sensor ring together. In fact, the higher speed of the lower rollers caused the carrots to move separately and untouchably. The number of carrots failing to go through the ring sensor was negligible. The following table shows the results of varying singulator inclination and roller speeds. The mean carrot speed through the sensing ring and the standard deviations are reported.

TABLE 1
Carrot Travel Speed Through the Sensing Zone
Roller Inclination

Roller Speed (rpm)	10.0		12.5		15.0	
	Mean (mm/sec)	Std. Dev. (mm/sec)	Mean (mm/sec)	Std. Dev.	Mean (mm/sec)	Std. Dev. (mm/sec)
700	786	78	1061	91	1171	117
800	866	76	1185	79	1191	117
900	954	93	1184	96	1300	91
1000	973	77	1228	97	1255	91

Description of Cooperation

The proposed cooperation between Israeli and Texas A&M researchers consisted of two major areas, the evaluation and development of the sensing system and the final evaluation of the completed inspection machine. Communication was to be done primarily with electronic mail. An Israeli visit to Texas in the second year of the project and a US visit to Israel in the third year were planned.

Effective cooperation occurred on the development of the vision based inspection system. The Israeli simulation of the fiber optic sensor had a direct impact on the work in Texas. The visit of Uri Peiper to College Station during the second year provided effective communication of the status of both sensing and handling systems.

Original plans were for Dr. Searcy to take the fully developed vision system to Israel for installation on the handling system. This was not achieved. Due to slower than anticipated development of both systems and the unstable political situation during the last months of the project, Dr. Searcy did not travel to Israel.

Evaluation of Research Achievements

As a result of this research, significant advances were made toward the automated grading of fresh market carrots. Although not all of the desired goals were met, the basis for the carrot grader has been established.

The goal of this research was the development of a carrot grading system that could operate at commercial rates. The two major requirements for this system were the sensing and handling systems. These will be discussed individually.

The original concept for the sensing system was the use of a ring of optical fibers connected to a line scan camera. Carrots were to pass axially through the ring, in order to inspect the entire surface. Specific characteristics that were to be measured included length, diameter, broken carrots, growth abnormalities, splits and blemishes, in decreasing order of priority. The target rate for processing the carrots was 5-10 carrots per second. In order to meet these goals, the following developments were required.

1. simulation of the optical fiber sensing ring
2. establishment of reflectance properties of normal and blemished carrot flesh
3. determination of optimum wavelengths for carrot irradiation
4. development of appropriate features that would discriminate between normal and defective carrots
5. development of image processing techniques to measure the carrot features
6. development of optimum classification technique that would provide the most accurate grading

7. design and implementation of computer hardware that would perform the image analysis and grading operations in 200 msec. or less
8. incorporation of the sensing system into the handling system for final testing

Of these eight tasks, the first five were completed, and are reported in this document. Task six was substantially completed at the end of the grant period and is reported here also. Additional work is ongoing and will be published in a doctoral dissertation and the Agricultural Engineering literature. Task seven has not been completed due to difficulties in integrating equipment from several manufacturers into a working system. The design of the imaging system is not reported in the previous section because a working system has not been achieved. In order to meet the speed requirements, an imaging board with a high speed digital signal processor, a line scan camera and a camera interface board were purchased with the intention that simultaneous processing could be done by the signal processor and host computer. Unfortunately, the imaging board manufacturer did not mention that the available software was designed for only sequential operation between the host and the signal processor. This has necessitated a much greater task of system integration. Although work will continue toward that integration, no results are available now. For this reason, task eight was also not completed.

The development of the handling system required the following sub-tasks:

1. design and construction of a feeding mechanism
2. design and construction of the singulation mechanism
3. design and construction of the conveying system to space the carrots by > 1 cm
4. design of a sensing area that will control the carrot path and speed on entrance and exit
5. design of a ejection mechanism that would register each carrot and eject them at the proper point
6. develop a carrot deceleration system that will dissipate the carrot's momentum without damage

The original concept for the carrot handling system was that the carrots would be singulated with a roller conveyor, oriented onto a narrow cross conveyor and passed through the sensing area. This concept was replaced by the method described previously and performed satisfactorily. There was no success in completing a system for the ejection and deceleration of the carrots after a classification decision was made.

In an additional development that was not part of the proposal, researchers at Texas A&M cooperated with carrot breeders to develop an image processing system that could be used to objectively evaluate the shape of carrot roots. The carrot breeders have traditionally graded carrots into shape classes using subjective human judgements. In an attempt to provide more consistency and objectivity in that evaluation, image processing was used to measure the bluntness of the carrot root shape. A neural network was developed to classify the carrots into 5 shape classes. This work is described in more detail in two papers entitled

Estimation of Tip Shape for Carrot Classification by Machine Vision and A Neural Network for Carrot Tip Classification (Appendices F and G).

List of Publications

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