

Development of a machine vision system for automatic date grading using digital reflective near-infrared imaging

Dah-Jye Lee^{a,*}, Robert Schoenberger^b, James Archibald^a, Steve McCollum^c

^a Department of Electrical and Computer Engineering, Brigham Young University, 459 Clyde Building, Provo, UT 84602, USA

^b Symmetron, LLC A Division of ManTech International Corporation, Fairfax, VA, USA

^c SG Growers, LLC., 3008 S. Branding Iron Court, Yuma, AZ 85364, USA

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Abstract

Quality evaluation of agricultural and food products is important for processing, inventory control, and marketing. Fruit size and skin delamination are two important quality factors for the date industry, especially for high quality dates such as Medjools. Unlike other near-infrared spectrometric approaches, the developed machine vision system uses reflective near-infrared imaging to evaluate date quality by analyzing two-dimensional images. This paper presents the development and test results of a machine vision system for automatic date quality evaluation for commercial production. Near-infrared imaging, vision algorithms, and a variety of operational details of the system, including cameras, optics, illumination, electronics, control, and fruit carrier are presented. The complete machine vision system has been built, field tested, and installed in a date packing facility. Relative to manual grading, the operational system results in improved grading accuracy and a substantial reduction in operating costs.

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1. Introduction

A typical date packing facility in the United States packs approximately 45–175 million individual dates each year. In California and Arizona, the date harvest lasts approximately two months and packing follows in a four-month window, generally from the end of August to the end of December. In virtually all packing facilities worldwide, dates are graded by hand. For a typical packing facility in the United States such as SG Growers (one of our project sponsors), the initial inspection stage requires about 80 workers to load, unload, and pre-sort the dates, and 55–60 workers are typically involved in the final grading and packaging. With labor costs increasing, the labor-intensive grading process constitutes a major expense for packers

and growers. Because the time window for processing is short, locating and hiring experienced workers is a challenging task for the date industry. The integration of a non-destructive automated grading system into a packing line has the potential of improving processing efficiency, reducing costs, and minimizing waste from false grading.

Researchers have developed a variety of nondestructive techniques for evaluating internal and external quality factors in agricultural and food products. These techniques include nuclear magnetic resonance (Chen et al., 1989 and McCarthy, 1994), X-ray for evaluating frost damage in citrus and hollow-heart in potatoes (Shahin and Tollner, 1997) and density and moisture content in apples (Upchurch and Throop, 1994), and near-infrared transmission and reflectivity. Despite the potential of these methods, high costs, substantial processing overheads, and safety concerns make them ill suited for use on a date packing line.

* Corresponding author. Tel.: +1 801 422 5923; fax: +1 801 422 0201.
E-mail address: djlee@ee.byu.edu (D.-J. Lee).

Visible (VIS) and NIR light has been used to determine a variety of factors in a wide range of agriculture and food products. A few examples for agriculture products include potatoes (Dull et al., 1991b), peaches (Peiris et al., 1998), nectarines (Slaughter, 1995), raisins (Huxoll et al., 1995), tomatoes (Shao et al., 2007), prunes (Slaughter et al., 2003), apples (Nicolai et al., 2006; Bellon et al., 1993; Moons et al., 1997), mangos (Subedi et al., 2007), and fruit firmness (Zude et al., 2006; Gomez et al., 2006). Other food products include meat and ground wheat (Hruschka and Norris, 1982; Delwiche et al., 1998; and Wang, 2004), cereal (Kays et al., 2005), whole wheat grains (Williams and Sobering, 1993 and Blanco and Villaroya, 2002), dietary fiber in food (Kim et al., 2006), and smoked salmon (Lin et al., 2003).

Relatively few papers on date quality evaluation have appeared in the literature. Based on the evaluation criteria, they can be categorized into: moisture (Dull et al., 1991a; Schmilovitch et al., 2003, 2006), water and soluble solids (Schmilovitch et al., 1997, 1999, 2000), firmness (Schmilovitch et al., 1995), and dryness (Wulfsohn et al., 1993).

Most related work described in the literature is based on the testing and evaluation of samples or at very slow processing speed (1–2 pieces per second). In contrast, this paper focuses on the design and development of the machine vision system for commercial production. Most NIR spectroscopy methods use wavelengths of NIR light at 1100–2500 nm and measure reflectance at just a few angles on a few points on the fruit surface. Our approach considers the NIR reflectance of the whole top fruit surface over wavelengths of 750–1200 nm to distinguish between normal skin and skin that is delaminated. To reduce costs, the system uses off-the-shelf optical and electronics components, yet is capable of grading 20 pieces of fruit per second for commercial production using a two-camera four-lane configuration. Although the system we describe is specific to the date industry, the technique employed could be adapted to the grading of other fruits and vegetables.

2. Materials and methods

2.1. Date processing and handling

Dates are first inspected manually after harvest to determine if they are ripe and ready for packaging or need further processing. Dates in the latter category are either sent

out to ripen in the sun, to a heated building to dry, or to a hydrating building to gain moisture. After the drying process, most dates ripen and become ready for packaging, although some end up in lower quality grades because of skin delamination that occurs as they dry.

Ripe dates are pasteurized before grading and packaging. This cleaning process is part of the packing machine and performed automatically as dates pass through the cleaning stage prior to grading and packaging. Dates are cooled to room temperature before grading, if necessary. Typically, dates are sorted into four grades (Jumbo, Extra Fancy, Fancy, Utility) based on size and skin delamination percentage. Typical grading criteria for each of these grades are listed in Table 1.

2.2. Design objectives and machine specifications

Our design objectives for an automatic date grading machine include:

- Non-destructive evaluation at commercial production speed
- Separation of fruit into pre-determined, user programmable grades
- Configurable grading criteria and adjustable grading speed
- Low system and operating costs

Machine operating specifications as defined by the Bard Valley Medjool Date Grower Association in California, USA include:

- Grading speed of 20 pieces of fruit per second
- Size grading based on fruit length or surface area according to user selection
- Combining fruit size and skin delamination percentage to determine the final grades
- Four user programmable grades (Jumbo, Extra Fancy, Fancy, and Utility)

2.3. System design

2.3.1. System components

The automatic date grading system (QuickSort) consists of four major components: optics, lighting, electronics, and carrier. Fig. 1 shows the block diagram of the grading sys-

Table 1
Typical Medjool date grading criteria

Grade	Descriptions
Jumbo/Premier	Larger than 56 mm and less than 5% skin delamination
Extra fancy	Larger than 56 mm but more than 5% skin delamination or between 46 mm and 56 mm and Less than 5% skin delamination
Fancy	Between 46 mm and 56 mm but more than 5% skin delamination or between 38 mm and 46 mm and less than 10% skin delamination
Utility	Smaller than 38 mm or more than 10% skin delamination

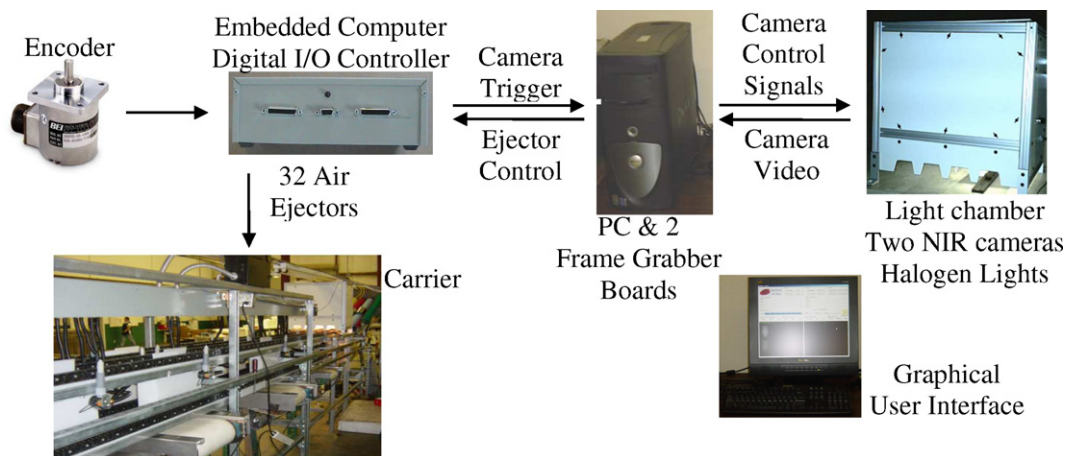


Fig. 1. System interconnect diagram of a 4-lane system.

tem and the interconnection of the components. An optical encoder outputting 2048 pulses per revolution is mounted on the carrier shaft that travels 1600 mm per revolution to provide a 0.78125 mm per pulse resolution for synchronizing the fruit carrier with image acquisition, processing, control, and product delivery tasks. Image acquisition and processing tasks are performed with Meteor-II PCI-bus frame grabber boards manufactured by Matrox Inc. and a commercial PC. Besides the PC for image processing and control, an embedded computer system is used to interface the encoder signal with the PC and to decode control signals sent from the PC to control 32 air ejectors that cause moving fruit to exit the carrier at grade-specific delivery points. The frame grabber board receives camera trigger signals from the embedded computer, digitizes camera images, and stores image data in computer memory. Computer vision software processes the digital images to determine grades and assign delivery locations. Graphical user interface (GUI) software developed with Visual C++ on the Windows XP platform allows the user to set parameters and perform system configuration and calibration.

2.3.2. Near-infrared sensor and optics

For date grading, images must have sufficient contrast between areas with normal and delaminated skin. Fig. 2a shows an image of a date with normal tight skin, while Fig. 2b shows a date with delaminated skin. Tight skin with little delamination is essential in dates of the highest quality; the quality diminishes as the fraction of delaminated skin increases. From these example images, it seems that color imaging could be used to detect the light brown areas of skin delamination as shown in Fig. 2b. However, natural ripe date colors range from dark and light reds to light browns (the same colors as delaminated skin). These normal variations in fruit color would make it difficult to use color imaging for skin delamination detection. For instance, normal fruit with light brown areas (spots) are easily mistaken as delaminated skin which exhibits the same colors. Since these light brown spots appear randomly on the fruit surface as does delaminated skin, color surface texture analysis does not provide consistent results. Also, color surface texture analysis would fail because a light brown fruit with skin delamination will not display distinguishable surface texture.

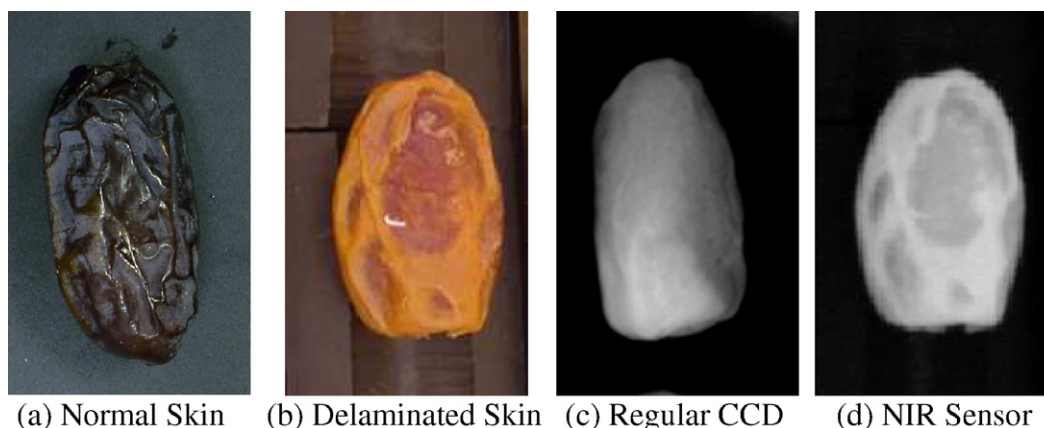


Fig. 2. Sample date images.

Fig. 2c shows a black and white image captured with a regular charge-coupled-device (CCD) camera in the visible spectrum. In this image, delaminated skin (in the lower region) is difficult to distinguish from normal skin. In comparison, the NIR image in Fig. 2d shows notable contrast between the delaminated (bright) and tight (dark) skin areas. Overall, NIR image is well suited for our application because it provides the required contrast for the detection of skin delamination.

As shown in Fig. 3, a typical CCD sensor has usable IR sensitivity – determined in practice to be 25% and above – only up to 850 nm. In contrast, NIR-extended CCD sensors extend the range of sensitivity and make it possible to use longer NIR wavelengths. Our system employs two Hitachi NIR-extended CCD cameras (each covering two processing lanes) that use interference filters to block light below 750 nm wavelengths and allow NIR image acquisition between 750 and 1200 nm. As Fig. 2d shows, this provides excellent contrast between the product and background, as well as between delaminated and tight skin areas.

A camera suitable for on-line inspection must possess certain features, such as a high-speed electronic shutter for acquiring images of fast moving objects, progressive scanning for full frame resolution, flexible gain and offset adjustments, and asynchronous reset for acquiring images precisely when desired. Short exposure times ensure image sharpness but also require more light. A shutter speed of 1/125 of a second was determined to be ideal, considering the available lighting and the moving speed of the fruit (approximately 406 mm per second). Each camera is fitted with an 8.5 mm lens and mounted 406 mm above the carrier, providing a 203 mm × 254 mm viewing area. Using these settings and optics, sharp and high quality NIR images can be acquired for analysis.

2.3.3. Light chamber

The cameras are housed in a light chamber to provide controlled and consistent illumination, as shown in Fig. 4. Eighteen 12 V 10 W halogen light bulbs are used

to provide uniform illumination. A pyramid-shaped plastic diffuser reflects and diffuses the light uniformly over the viewing area below the light chamber. The interior of the light chamber is white to maximize the amount of lighting reaching the diffuser.

2.3.4. Electronics

As shown in Fig. 1, the embedded computer receives encoder pulses from the encoder, divides them by 4 and generates a 5 V TTL signal every 3.125 mm for fruit tracking and delivery, and divides them by 100 to generate a camera trigger signal every 78.125 mm to initiate the image acquisition. After every image acquisition and processing, the PC sends control data for the 32 ejectors to the embedded computer through an RS-232 serial connection. The embedded computer then decodes the ejector control data and activates the ejectors at the specified time, as determined by the fruit tracking and delivery signal. The enclosure that houses the embedded computer also houses a digital input/output board. The encoder signal is received through one of the 16 digital input ports. Control signals for the ejectors are sent through 32 digital output ports.

2.3.5. Carrier

The patent pending singulation, imaging, and delivery sections of the date grading system are shown in Figs. 5 and 6. The singulation section arranges the dates into single file (Fig. 5a) by causing them to fall onto the u-shaped plastic carrier one at a time (Fig. 5b). The carrier causes the singulated dates to pass under the light chamber where they are imaged by the cameras (Fig. 5c). Images are transferred to the PC for processing, and fruit grade is determined immediately after processing. The grade and location of each date is then recorded in a memory array in the PC. The index of this memory array is incremented as each fruit tracking and delivery signal is generated by the embedded computer and is received by the PC. The PC sends ejector control data to the digital I/O board corresponding to the desired drop of each date (Figs. 6a and b). Fig. 6c shows the entire section of the delivery system.

2.4. Processing methods

2.4.1. Image processing

Images are preprocessed to detect the presence, size, and type of fruit. The images of dates are then processed to convert image characteristics into values quantifying fruit size and skin delamination percentage. The block diagram in Fig. 7 summarizes the processing flow of the three major tasks in image processing: fruit detection and size measurement (left column of processing steps), tight skin fruit detection (middle column), and skin delamination evaluation (right column). Fig. 8 depicts an example processing result and is used to describe these three tasks.

Fig. 8a shows an image of a typical date with slight lamination. The high contrast between the fruit and background allows the user to manually select a threshold

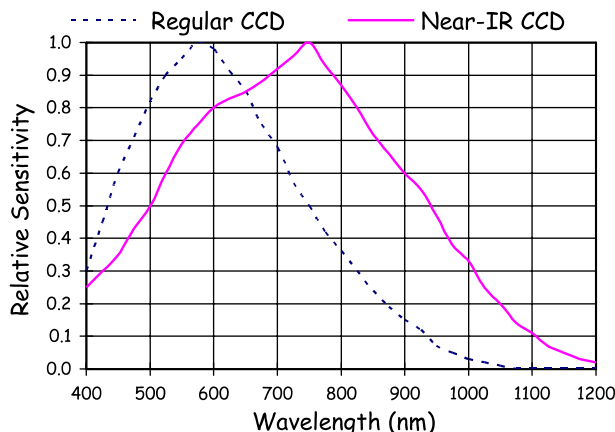


Fig. 3. Extended near IR sensitivity of a near IR-extended CCD sensor.

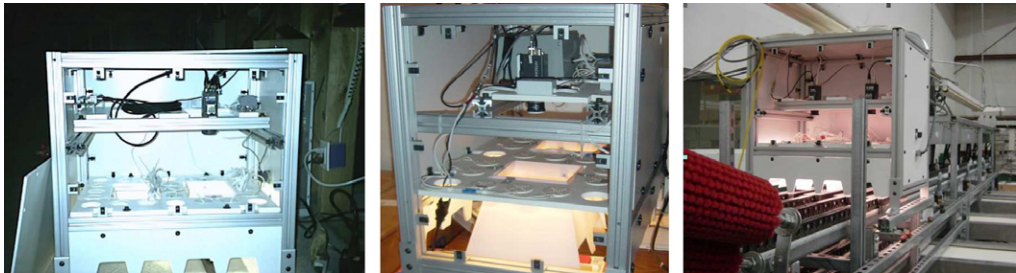


Fig. 4. Interior and exterior of the light chamber.



Fig. 5. (a, b) Singulation section and (c) the imaging station of the date carrier.



Fig. 6. (a, b) The ejectors and (c) the delivery of the date carrier.

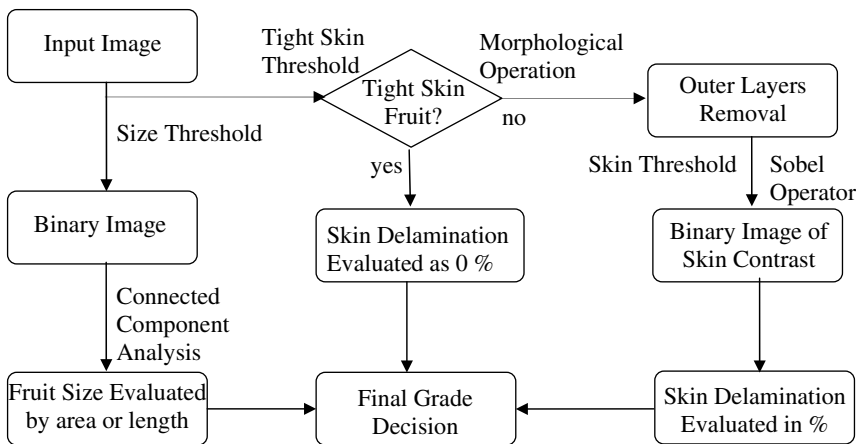


Fig. 7. Image processing algorithm block diagram.

that separates the image into two regions corresponding to fruit and background before grading. The resulting binary image is shown in Fig. 8b with fruit pixels represented by

an intensity value of 255 and background pixels by an intensity value of 0. Connected component analysis is then applied to determine the size of the fruit region measured

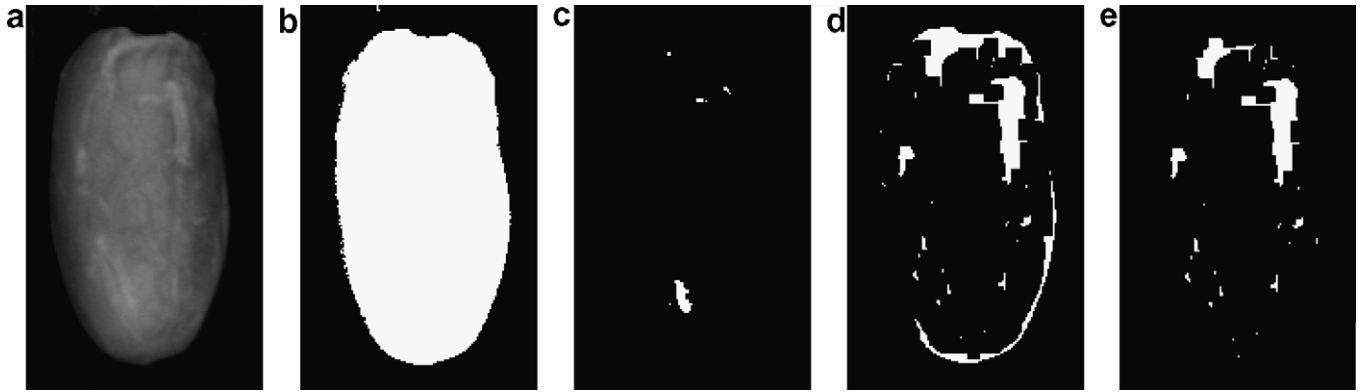


Fig. 8. Jumbo date with slight skin delamination.

by the number of pixels. If the region size is greater than a predetermined value (e.g., 3000 pixels), the system reports that a date is detected and it records the bounding box of the fruit in the image coordinates obtained from the connected component analysis so that its location can be accurately tracked. Using a fruit with known size in mm, the height of its bounding box measured in number of pixels is used to calculate the millimeter-per-pixel ratio. Using the millimeter-per-pixel ratio, the size of the fruit can be calculated either by length in millimeters or by area in square millimeters depending on user preference as selected in the graphical user interface.

Fruit can be dry and hard or moist and soft. They are considered to have the same quality because grading is based only on fruit size and skin delamination measurements. Dry fruit are a result of drying before fully ripe. They have very tight skin and light red colors (lighter than fully mature fruit) on the entire fruit surface. The NIR imaging of these fruit have brighter intensity values than fully mature fruit. The second major task of image processing is to detect dry and very tight skin fruit. We apply a “tight skin” threshold to the original image to obtain a binary image as shown in Fig. 8c. If the total area of the binary image exceeds a user selected percentage of the fruit surface area as shown in Fig. 8a, then the fruit is classified as having tight skin and assigned a 0% skin delamination as

shown in Fig. 7. Fruit not classified as having tight skin receive further skin delamination evaluation processing (the right column in Fig. 7).

As previously noted, simple techniques that threshold on intensity values are not suitable for the detection of skin delamination. Our vision system uses the Sobel operator to detect the edges of greatest contrast or change in intensity in each image, which is a good representation of delaminated skin as shown in Fig. 8d. Sensitivity of skin delamination detection is adjusted by a user-selected skin threshold (a threshold for the Sobel operator). Despite the uniform illumination of the fruit surface within the light chamber, the curvature of the fruit surface causes a slight intensity gradient near the edge of the date that could be mistakenly detected by Sobel operator as delaminated skin. Five iterations of the morphological operation of erosion are applied to the original binary image shown in Fig. 8b to remove a few outer layers of Fig. 8d that could potentially bias the measurement. The slightly smaller binary mask that results is logically ANDed with the contrast image shown in Fig. 8d to generate the final skin delamination image shown in Fig. 8e. From this image, a skin delamination percentage is then calculated as the ratio of the delaminated area to the area of the slightly smaller mask. Figs. 9–11 show corresponding images of three dates that vary in size and skin delamination percentage.

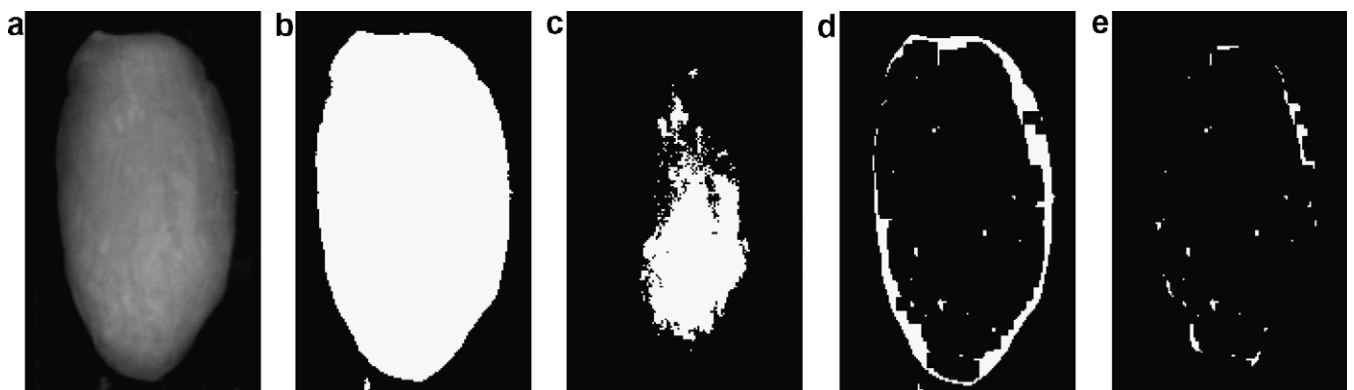


Fig. 9. Jumbo date with no skin delamination.

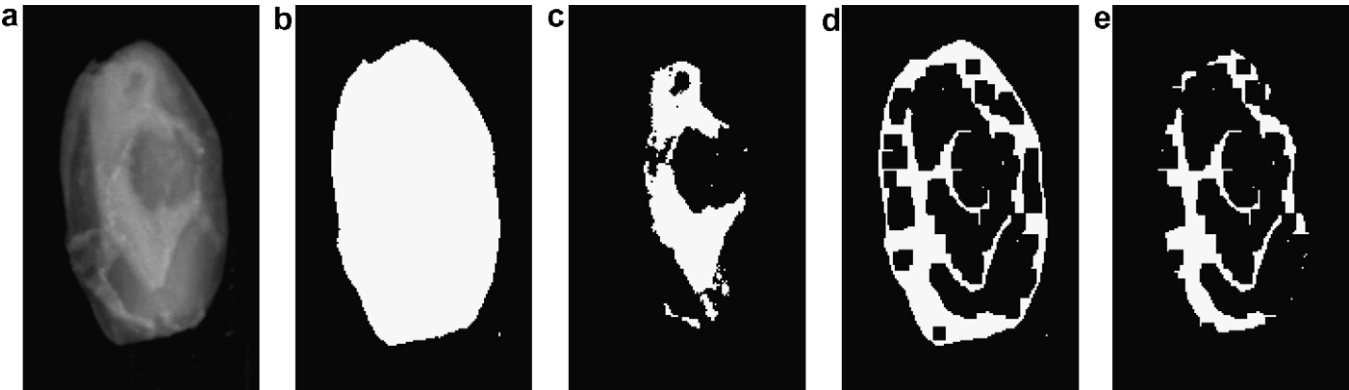


Fig. 10. Medium date with severe skin delamination.

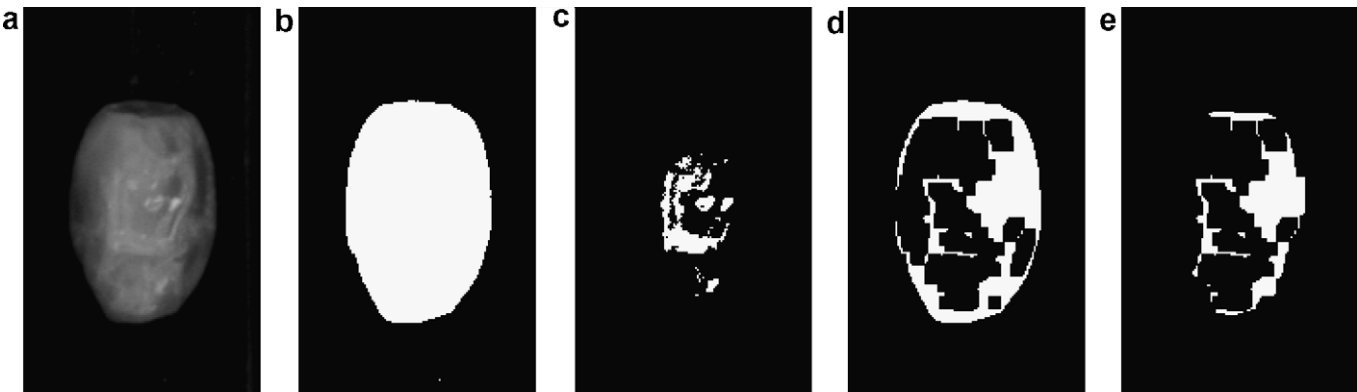


Fig. 11. Small date with severe skin delamination.

2.4.2. Final grade assignment

As mentioned in Section 2.1, typical grading criteria used by the Bard Valley Medjool Date Grower Association in California, USA are listed in Table 1. To allow the user to enter similar grading criteria, a two-dimensional matrix is designed to set a preferred set of grading criteria (size and skin delamination) as shown in Table 2. The left column is for fruit length in mm and the top row is for skin delamination in percentage. For example, fruit longer than 56 mm and with less than 5% skin delamination will be assigned a final grade “A” (Jumbo grade). Fruit with size between 38 and 46 mm and less than 5% skin delamination or between 46 and 56 mm and 5–10% skin delamination will be assigned a final grade “C” (Fancy grade). As shown in Table 2, the current system is designed to allow the operator to enter 4 size and 4 skin delamination cut-off points, which can potentially grade the fruit into 25 final grades

(based on the resulting 5 × 5 matrix). Normally, only 5 grades (A to E) are assigned (with grade E, a “trash” grade, being the lowest). Of course, more grades can be assigned using a more complicated matrix as long as the machine has enough outlets to take them. Each of these 5 grades can then be assigned to one or more drops (outlets). The current system has a total of 8 drops to accept these 5 grades. Grades with higher volume will sometimes be assigned 2 or 3 outlets.

2.4.3. Tracking and delivery

Once the grade of a date has been determined, it must be tracked along the packing line until the carrier transports it to its destination and the ejectors deliver the fruit. As illustrated in Fig. 5c, the carrier transports the fruit through the imaging area in single file but with random spacing. Unlike most product handling systems that use pockets or cups on the carrier to maintain fixed spacing to simplify synchronization with image acquisition, this system allows dates in each lane to be presented at unknown and random locations on the carrier as it passes the imaging window. A novel Product Tracking and Delivery (PTD) mechanism (patent pending) was developed to accurately track fruit location after leaving the viewing area and to deliver each date to the appropriate take-out conveyor belt by ejecting it at the right time.

Table 2
A grading matrix for final grade assignment

	<5%	<10%	<15%	<20%	
>56 mm	A	B	D	D	E
>46 mm	B	C	D	D	E
>38 mm	C	D	D	D	E
>25 mm	D	D	D	D	E
	E	E	E	E	E

A new camera image is acquired for every 78.125 mm of forward motion by the carrier. (The exact value is programmable.) Image acquisition is triggered by a high-resolution optical encoder attached to the carrier shaft. Although the camera's field of view covers 203 mm along the direction of movement, only a subset of each image is analyzed; only fruit that are entirely within or that are entering the top 78.125 mm of the view area are processed in a given image. As the following example illustrates, this ensures that every piece of fruit is analyzed, even with random spacing.

Fig. 12 depicts the state of a processing line captured in two consecutive images as the fruit pass under the light chamber. The upward arrow on the left of the figure shows the direction of motion of the carrier. In the first image (on the left), fruit pieces 1–4 are entirely or partly in the camera's field of view, but only pieces 1 and 2 meet the conditions for analysis in this frame: piece 1 lies entirely within the 78.125 mm region atop the image, and piece 2 is just entering. In the second frame, the carrier has advanced so that fruit pieces 2–5 are in the field of view. In this case, only pieces 3 and 4 will be processed. Piece 2 has partially exited the view area (and was therefore processed in the previous frame), and piece 5 has not yet entered the 78.125 mm top region. Note that each date will be processed in its entirety in exactly one image.

This specially designed acquisition and processing system captures more images than strictly necessary, but the approach allows the system to handle randomly spaced fruit without missing a single piece. This, in turn, simplifies the mechanical design and maintenance of the carrier. When fruit images are analyzed, their size, skin quality, and location are recorded. Each piece is assigned a grade

according to user-selected settings and its location is tracked by software based on the encoder signal from the carrier. The software causes the digital input/output board to send an activation signal to the air ejector when the fruit reaches its designated drop or outlet.

2.4.4. Calibration

One critical step that must be completed before the system can be used for production is system calibration. To achieve a high processing volume, most installations will use multilane configurations, and the system must grade fruit consistently within each individual lane and between different lanes. System calibration involves two types of adjustment that affect grading: the adjustment of thresholds and the adjustment of grading parameters (Table 2). Due to slight lighting variations and acquisition noise, thresholds may have to be set differently for each lane to achieve consistency over multiple lanes. For example, in a four-lane system, the two outer lanes are usually slightly darker than the inner lanes and their thresholds must be set accordingly.

The system is calibrated by first selecting 50 pieces of fruit that can be evenly categorized into 5 grades by experienced human graders. When properly configured, the system will grade and deliver 10 dates to each of 5 different drops regardless of which lane they travel in or the order in which they occur. Proper calibration is ensured by completing the following steps:

1. Select grading parameters (size and skin delamination percentage settings in Table 2) and designate a specific drop for each grade.
2. Adjust the three image processing thresholds for a given lane until the desired grading results are obtained when all 50 dates are transported in that lane. (Recall that the thresholds affect classifications of fruit size, dry and tight skin, and skin delamination).
3. Repeat Step 2 for each remaining lane.

Once the thresholds are properly adjusted and calibration is complete, the system will be able to use one set of grading parameters that specifies both size and skin delamination percentage as shown in Table 2 to obtain consistent grading of results across all lanes. Adjustments in individual lane thresholds will compensate for variations in lighting and noise.

3. Results and discussion

3.1. Accuracy and consistency testing

Grading accuracy is determined using a procedure similar to that used for system calibration. Twenty five pieces of fruit are carefully selected by experienced human graders from each of four commonly used grades (not including the trash grade) for Medjool dates: jumbo, extra fancy, fancy, and utility. Typical criteria for each of these grades are

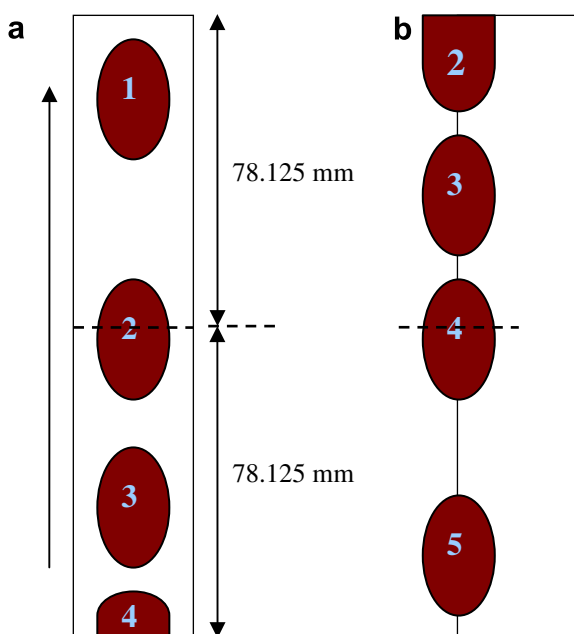


Fig. 12. Product tracking and delivery (a) previous frame (b) current frame.

listed in Table 1. Based on repeated tests and careful analysis, we determined the following:

- Large fruit (larger than 56 mm) usually have less than 2% skin delamination.
- Smaller fruit (between 46 mm and 56 mm in length) have more skin delamination than large fruit on average, sometimes approaching 5%.
- Size grading has an accuracy of ± 2.5 mm.
- Skin delamination grading is not consistent as shown in Table 3 because only the top side is inspected.

We conducted tests designed to evaluate intra-lane accuracy and inter-lane consistency of the system. For both test runs, the grading parameters were set according to the criteria listed in Table 1. In each experiment, the 100 hand-selected sample dates were either graded three times by each individual lane or twelve times by the whole four-lane machine.

For the intra-lane accuracy experiment, fruit pieces were hand-fed to the system one lane at a time in grade-specific order, with all 25 dates of a given grade appearing before any dates of the next grade. Table 3 reports the results of this experiment in terms of the number of dates assigned to each grade for each lane. The grading accuracy of each individual lane was determined with this test. Note that a perfect grading system would result in 75 dates in each grade. The rightmost column reports the total count of fruit assigned to each grade by the machine vision system. For example, 300 jumbo dates were imaged and processed (25 dates per run, 3 runs per lane, and 4 lanes), and 290 dates were graded by the system as jumbos. Similarly, too few dates were assigned to the fancy and utility grades, while the extra fancy grade received 28 pieces from other grades.

For inter-lane consistency testing, the 100 samples of different grades were mixed together and graded twelve times (approximately 300 pieces per lane, on average) by randomly spreading dates over the four lanes, all of which were operating simultaneously. The overall system consistency across all four lanes was determined with this test. As in the previous experiment, a count of the total pieces of fruit appearing at each drop location from each lane was kept. The resulting grade distribution was very close to the overall grade counts in Table 3, indicating that the overall grading consistency of the system differs little from the accuracy of individual lanes. Unlike the intra-lane test that had the same number of dates for each lane, this test

had different numbers of dates for each lane because dates were spread randomly over the four lanes. To present the results more clearly, Table 4 reports the results as a percentage of the dates of each grade that were graded correctly in each lane instead of number of dates. As can be seen, jumbo dates have the highest grading accuracy since skin delamination is uncommon and size grading is very accurate. Fancy and utility grades have lower grading accuracy because skin delamination grading accuracy is affected by inspecting only the top side of the fruit surface. The rightmost column in Table 4 reports the average accuracy for each grade over all four lanes.

3.2. Production test

Another performance test was conducted while the system was in full commercial production. This test was completed by comparing the accuracy of human grading with that of the system. Human grading accuracy was evaluated in a conventional manual facility, in which workers line up on both sides of a slow moving conveyor belt, visually grade the fruit, and separate them into bins of different grades. To obtain a representative sample of typical work, the workers were not informed about the experiment. Five experienced graders evaluated the grading accuracy of fruit in each grading bin multiple times during a regular 8 h shift. It was determined by these five experienced graders that average human grading accuracy ranges from a low of 60% to a high near 72%. This low human grading accuracy was most likely due to a variety of reasons including fatigue, concentration, experience, and fruit quality, etc.

Tests of the system's grading accuracy were conducted in a similar manner, with the system running at full production speed, i.e., close to 5 pieces of fruit per lane per second. This is equivalent to about 576,000 pieces of fruit per 8 h shift for one 4-lane system. Experienced graders evaluated the grading accuracy at all grade drops multiple times during the shift. The consensus was that the system's grading accuracy typically falls in the range from 74% to 79%. The main reason that production accuracy is lower than measured accuracy (87%) in offline tests presented in Table 4 in Section 3.1 is that fruit in real production vary in their orientation relative to the carrier, unlike the hand-placed fruit in offline tests. This angle variation affects the determination of their size and lowers the grading accuracy. A better singulation design could potentially alleviate this problem.

Table 3
Result of lane and grade precision test (intra-lane accuracy)

	Lane 1	Lane 2	Lane 3	Lane 4	Grade count
Jumbo	72	73	72	73	290
Extra fancy	81	82	85	80	328
Fancy	74	72	71	73	290
Utility	73	73	72	74	292
Total lane count	300	300	300	300	1200

Table 4
Result of overall system precision test (inter-lane accuracy)

	Lane 1	Lane 2	Lane 3	Lane 4	Grade accuracy
Jumbo (%)	94.6	96.0	96.0	93.3	95.0
Extra fancy (%)	90.7	93.3	92.0	88.0	91.0
Fancy (%)	77.3	80.0	81.3	78.7	79.3
Utility (%)	82.7	86.7	84.0	82.7	84.0
Lane accuracy (%)	86.3	89.0	88.3	85.7	87.3

Although the system improves average grading accuracy by only about 10%, the financial benefit is nevertheless significant. If desired, companies could improve on the accuracy of machine grading by adding a few experienced graders to re-examine the machine-graded fruit. The automation would thus allow employers to retain experienced workers while reducing the challenge of finding a large number of temporary workers each season.

4. Discussion

This paper discusses the challenges and detailed design decisions involved in the creation of an automated date grading system. A vision system was designed to measure fruit size and skin delamination based on digital reflected near-infrared imaging. All design aspects including electronic hardware, software, optics, lighting, mechanical, and control are discussed. Detailed image processing techniques for real-time fruit quality evaluation are introduced. System specifications, the calibration procedure, and accuracy and production test results are discussed in detail. The production test has shown an improvement in grading accuracy of approximately 10% over human grading, while at the same time reducing labor costs by almost 75% (requiring just 15 rather than 60 workers or equivalent to \$2800–\$3600 per day depending on the workers' hourly rates) and shortening the processing time for grading.

A few shortcomings of this grading system have been identified. To simplify the mechanical design and maintenance, the fruit carrier was designed to allow visual inspection only of the top of the fruit. Statistically, inspection of both the top and bottom of the fruit could provide a marginal improvement in grading accuracy, but the feasibility and cost-effectiveness of such an enhancement remains to be investigated. Shortcomings in the carrier design have been observed with respect to both fruit singulation and orientation. Inefficient fruit singulation results in an occasional "double", two pieces of fruit in the same lane that overlap or touch, and this negatively affects both grading and delivery. Similarly, variations in the orientation of the fruit negatively affect the measurement of size and complicate delivery. Fruit overlapping and orientation variation are the two main reasons that the system cannot achieve the same 87% accuracy as seen in offline tests for real production.

Possible future work to improve system performance includes the use of mirrors to allow the inspection of more of the fruit's surface, as well as an improved mechanical design for fruit singulation. The vision algorithms and the carrier could be modified to accommodate other types of fruit with different sizes and shapes. Depending on the desired grading criteria, the image sensors could be changed from NIR to VIS or color. Although this paper focuses on automatic date grading, much of the underlying system, including software, optics, and the tracking and delivery mechanism, could be adapted to other fruits and vegetables.

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