USE OF INERTIAL PROPERTIES TO ORIENT TOMATOES

P. Motabar, A. M. Lefcourt, U. Tasch, M. S. Kim, R. Rostamian

ABSTRACT. *Recent theoretical and experimental results have demonstrated that it is possible to orient quasi-spherical objects such as apples by taking advantage of inertial effects during rotation. In practice, an apple rolled down a track consisting of two parallel rails tends to move to an orientation in which the stem/calyx axis is parallel to the plane of the track and perpendicular to the direction of travel as angular velocity increases. In this study, orientation tests were conducted using hothouse, globe, and plum tomatoes to demonstrate that quasi-spherical produce other than apples could be oriented using inertial effects. In addition, to allow testing of theoretical predictions regarding effects of shape on the orientation process, the three tomato cultivars were selected to correspond to the three shape classes used to for theoretical analyses: elongated, spherical, and squat. Single-pass and three-pass orientation rates for hothouse and plum tomatoes were about 90% and 100%, respectively. For the globe tomatoes, which tended to be "perfectly" spherical and which had uniform internal density distributions, three-pass orientation rates approached 90%. These results support the theoretical finding that it would be relatively easy to orient elongated and squat objects, and more difficult to orient spherical objects. In conclusion, rolling quasi-spherical produce down tracks consisting of two parallel rails is a commercially viable method for orienting such produce for imaging.*

Keywords. *Apple, Inertial effect, Machine vision, Orientation, Tomato.*

Theoretical (Narayanan et al., 2008a) and experimental (Lefcourt et al., 2009; Narayanan et al., 2008b) results demonstrate that it is possible to orient quasi-spherical objects with an axis of axial symmetry using inertial properties. The ability to appropriately orient fruit such as apples for imaging reduces the number of imaging perspectives needed to view the entire surface of a single object (Reese et al., 2009) and enhances the ability to differentiate stem and calyx regions from problem sites such as bruises (Bennedsen and Peterson, 2005). Improved imaging capabilities can enhance the ability to sort items for desirable and undesirable attributes. Because of the potential benefits of appropriately orienting fruit for imaging, a number of other methods to orient fruit have been investigated (Brown et al., 1988; Whitelock et al., 2006). These other methods are primarily based on the shape of objects and the effects of gravity. More detailed discussions of other methods used to orient fruit can be found in prior publications on the use of inertial properties for orienting apples (Lefcourt et al., 2009; Narayanan et al., 2008b). Tests of the ability to orient apples were conducted by rolling apples down test tracks consisting of two parallel rails. As angular velocities increased, apples tended to move to an orientation in which the stem/calyx axis was parallel to the plane of the track and perpendicular to the direction of travel.

The current study was designed to demonstrate that produce other than apples could be oriented using inertial properties and to allow more detailed testing of theoretical predictions regarding effects of shape on the ability to orient objects based on inertial properties. Theoretical results suggested that it would be relatively easy to orient elongated and squat objects, but that it would be difficult to orient spherical objects (Narayanan et al., 2008a). An attempt to test this theoretical prediction using apples was not conclusive, as the shape characteristics across apples and apple cultivars were too similar (Narayanan et al., 2008b). For this study, the three tomato cultivars chosen for testing were selected to match the three theoretical classes of elongated, squat, and spherical shapes.

An important observation made during tests with apples is that the orientation process is random (Lefcourt et al., 2009; Narayanan et al., 2008b). As the motivation for developing an orientation process is to facilitate sorting, it is thus theoretically feasible to use the sorting mechanism to recycle items that were not oriented appropriately for imaging. To address this possibility, each tomato was rolled three times to allow calculation of net orientation rates given the possibility of zero, one, or two recycle events. For example, if the single-pass rate for successful orientation is 80% and a maximum of two recycle passes are allowed for tomatoes that were not yet

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successfully oriented in a prior pass, the net orientation rate is 99.2%, with 20% and 4% of the tomatoes recycled once or twice, respectively.

METHODS AND MATERIALS

IMAGE ACQUISITION

Videos of tomatoes rolling down tracks were acquired using a monochrome camera (model XC-HR50, Sony Electronics, Inc., Park Ridge, N.J.) equipped with a 7.5 mm lens (Rainbow, s7.5 mm, f/1.4, Rainbow, Inc., Costa Mesa, Cal.) and a frame-grabber (model PCI-1409, National Instruments, Austin, Tex.). Full-frame (640 × 480 pixels) images were acquired at 60 frames s^{-1} using an exposure time of 1/500 s. Image acquisition was triggered using a remote contact switch attached to a digital I/O board (model CIO-DIO24, Measurement Computing Corp., Middleboro, Mass.). The videos were captured in AVI format using software written in Visual Basic 6 (Microsoft Corp., Redmond, Wash.).

Halogen lights (model Tota, Lowell, Brooklyn, N.Y.) were mounted on two light stands (Promaster LS-3, Photographic Research Organization, Inc., Fairfield, Conn.) with 500 W and 300 W lights placed 2.3 and 0.7 m above the floor, respectively (Narayanan et al., 2008b). Light stands were placed 1.2 m perpendicular to each end of the track. Existing fluorescent room lights provided additional lighting. A black backdrop (3.05 × 3.66 m; Botero, Bogota, Colombia) was mounted on a backdrop support system (model SP93, Lowell) and placed behind the track. The backdrop was suspended along its width with the excess material of the backdrop forming a 3.12 m wide × 1.19 m deep base on the floor (fig. 1). The camera was mounted 3.45 m from the track and 2.59 m from the floor. The lower and upper ends of the track were 10 and 64 cm above the floor, respectively.

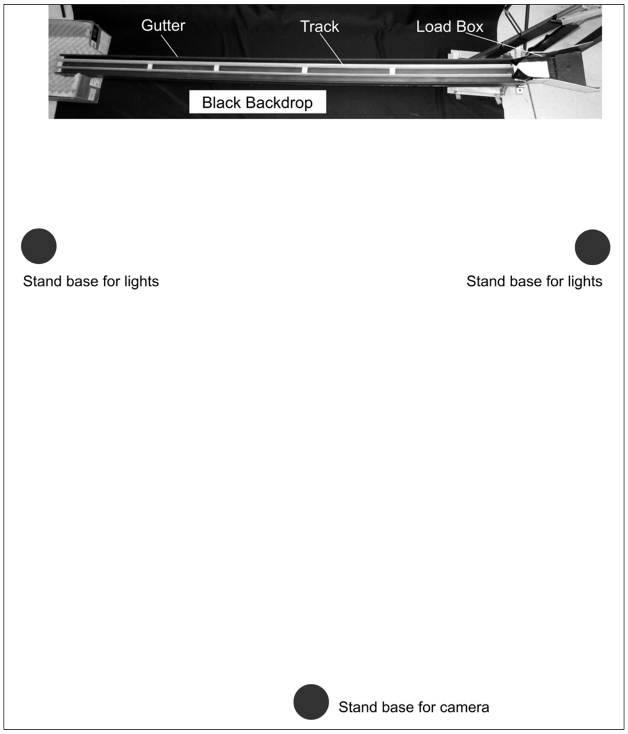

Figure 1. Overhead view of a typical test setup, which consisted of a box used for loading tomatoes onto tracks, and a track mounted in a gutter. Videos were acquired using a frontal view.

TOMATOES

Three tomato cultivars were used for tests (fig. 2). Plum and globe tomatoes were purchased from Coastal Sunbelt Produce Co., Savage, Maryland, and hothouse tomatoes were purchased from Cefalu G & Bro Wholesale Produce Market, Jessup, Maryland. Tomatoes were stored in an available apple storage refrigerator at 5°C. Fifty green, unripened, tomatoes were randomly selected for each cultivar, omitting only visibly defective tomatoes. The stem and blossom ends were darkened using a black marker to ease visual detection of these regions. Each tomato was weighed using a balance (±0.1 g; Explorer, Ohaus Corp., Pine Brook, N.J.). Height and width were measured using calipers (Brown & Sharpe Mfg. Co, Providence, R.I.), and the longitudinal circumference and transverse circumference were measured using an apple gauge (±0.25 mm; Cranston Machinery Co,, Oak Grove, Ore.; Whitelock et al., 2006). Tomato shapes were characterized using ratios of length to width and longitudinal to transverse circumferences. Tomato characteristics were summarized using distribution histograms with intervals of 15 g for mass and 0.1 for ratios.

TEST TRACK DESIGN

A full set of initial trials was conducted employing a wooden track previously used for testing apple orientation (Narayanan et al., 2008b; fig. 3, top). Results were not satisfactory. The problems with successful orientation of the tomatoes were cultivar dependent. A series of tracks was constructed and tested for each cultivar in an attempt to produce an appropriate track for each cultivar (fig. 3). The tomatoes, about eight for each cultivar, that were the most difficult to orient in the initial trials were used to optimize track designs. A few of these tomatoes were damaged during this development process and were replaced by similarly shaped tomatoes for final testing.

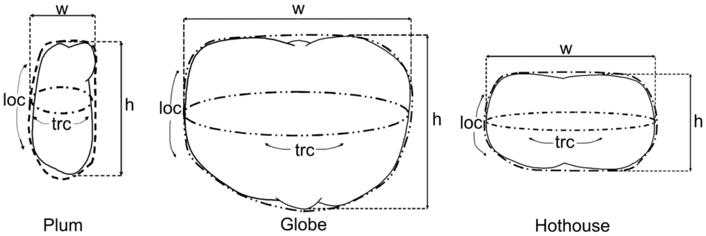

Figure 2. Shape characteristics and measurements for typical plum, globe, and hothouse tomatoes shown with the stem at the top center. Calipers were used to measure height (h) and width (w), and an apple gauge was used to measure the longitudinal circumference (loc) and transverse circumference (trc).

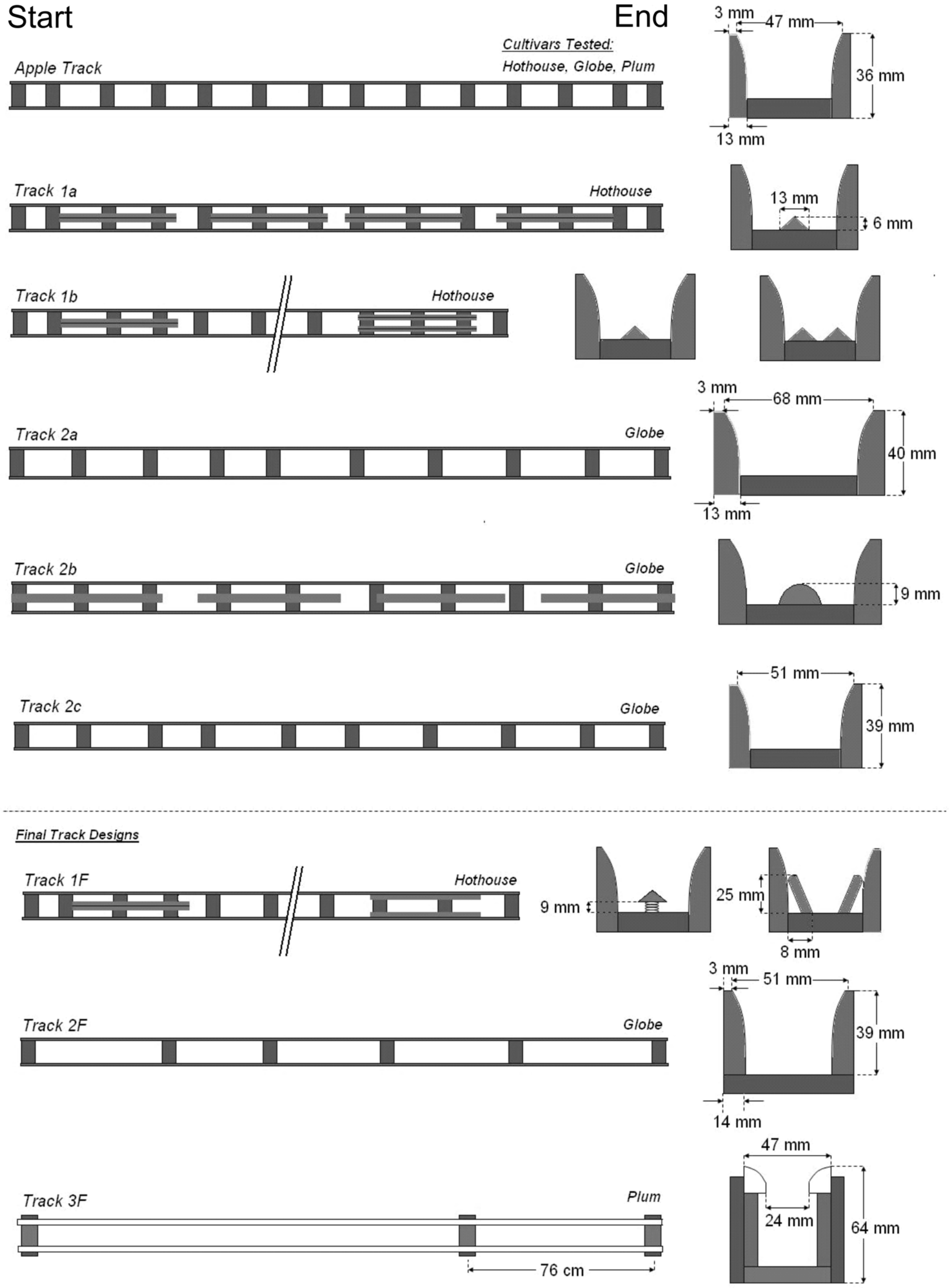

Figure 3. Chronological progression of track designs for the three tomato cultivars. Dimension information is displayed only when it differs from the track above, and final track designs are shown below the dotted line.

The tracks were constructed using wooden molding for rails with the exception that the rails of the final track for plum tomatoes were polyvinyl chloride rather than wood. The tracks were 3.05 m (10 ft) in length. The cross-section of the molding used for the rails and the placement of cross-brace supports are shown in figure 3. The tracks were placed in a wooden gutter that gently returned errant tomatoes to the track. The gutter was angled at 11°, and the track was supported at both ends of the gutter by wooden blocks. To increase compliance, springs were inserted between the track bottom and the top of the support blocks for the final hothouse and globe tracks (fig. 4).

EXPERIMENT

To load tomatoes onto a track, an open top-loading box lined with thin foam was attached to the start of the track (fig. 1; Lefcourt et al., 2009). The loading box funneled tomatoes onto the test track. Tomatoes were loaded into this box using a "dice cup" that consisted of a large plastic coffee canister lined with thin foam (Lefcourt et al., 2009). The foam extended 30 cm from the top edge of the canister. Each tomato was "rolled" in the dice cup for 3 s before being poured into the loading box. Tomatoes at the end of the track were captured using a foam-lined box. This box obscured the very bottom of the track, thus reducing the effective length of the track that could be observed or imaged. Video image

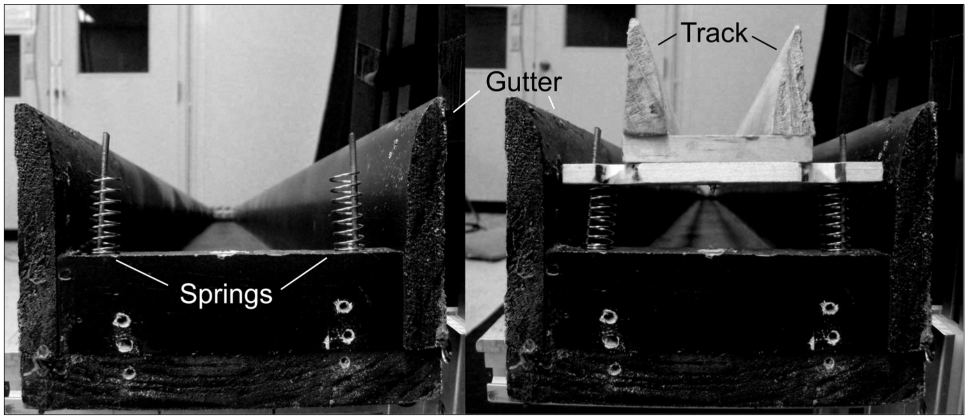

Figure 4. Spring supports were added to the start and end of tracks used for hothouse and globe tomatoes. The springs are shown uncompressed before (left) and compressed after (right) track placement.

acquisition was started manually each time a tomato was poured into the top-loading box, and three videos were acquired for each tomato. For each of the three replicate videos, the orientation of the tomato on loading was random due to the use of the dice cup.

ANALYSIS

Modified versions of software developed in-house using Visual Basic 6 were used to identify frames in which the stem or blossom end of a tomato was fully visible (Lefcourt et al., 2008). Unfortunately, the previously developed automated algorithm to detect the stem or calyx of apples did not reliably detect the stem or blossom end of tomatoes. The modified software allowed the videos to be displayed at any desired frame rate and to be paused by clicking a mouse button. Once a video was paused, a slider control was used to select individual frames for viewing. For frames in which the stem or blossom end was fully visible, the pixel coordinates of the center of the stem or blossom end could be recorded by placing the cursor on the center and then clicking a mouse button. The black markings added to the stem and blossom ends facilitated this process. A tomato was considered to be oriented for any contiguous series of frames in which the stem or blossoms end was fully visible in every frame and the number of frames in the series was three or more.

Orientation results were summarized using histograms showing percentages of tomatoes oriented within sequential 20-pixel horizontal intervals, which given the 4.55 mm pixel resolution results in intervals approximately 91 mm wide. Results were analyzed in terms of horizontal distances traveled and not in terms of actual distances traveled down the tracks. The horizontal distances are slightly shorter than the corresponding actual distances as the tracks were angled downward and vertical displacements were ignored. The algorithm used to determine if a tomato was oriented looked for the first frame in which the tomato appeared to be oriented. The corresponding interval was determined by looking at the location of the center *x*-coordinate of the tomato in that frame. If the center *x*-coordinate of the tomato was equal to or greater than the starting coordinate of an interval and less than the corresponding ending coordinate, then the tomato was considered to be oriented starting with that interval. The video was then examined on a frame-by-frame basis to determine the last frame in which the tomato remained oriented. The interval corresponding to this last frame was determined as above. The tomato was considered to be oriented for all intervening intervals.

Data were analyzed assuming that a commercial sorting system could allow tomatoes that were not successfully oriented to be recycled one or two times. To determine single-pass orientation rates as a function of distance traveled, the means and standard deviations of percentage orientation rates were calculated for each horizontal interval using all the data. To model the case in which a single recycling event might be allowed, analyses were based on successful orientation rates for each of the three possible combinations of two of the three replicate passes. For example, one combination included data from pass one and pass three, i.e., an individual tomato was considered to be oriented at a given interval if it was oriented at that interval for either pass one or pass three. To model the case in which two recycle events might be allowed, data were examined to see whether a tomato was oriented at a given interval for at least one of the three passes.

RESULTS

TOMATO CHARACTERISTICS

Figure 5 shows the mass distribution of the tomatoes used in this study. The mass of the plum tomatoes ranged from 48.9 to 125.5 g with a mean of 82.1 ±15.4 g. The hothouse tomatoes were slightly heavier and ranged from 62.4 to 153.4 g with a mean of 109.3 ±22.1 g. The mass distribution for globe tomatoes was skewed to the left and ranged from 143.8 to 225.2 g with a mean of 185.9 ±23.9 g.

The length-to-width ratio distribution for each cultivar is shown in figure 6. The plum tomatoes were elongated, with a mean ratio of 1.27 ±0.07. The hothouse tomatoes were squat, with a mean ratio of 0.93 ±0.03. The globe tomatoes were spherical, with a mean ratio of 1.01 ±0.04. Figure 7 displays the distributions of the longitudinal-to-transverse circumference ratio for the selected tomato cultivars, which were similar to the length-to-width ratio distributions.

ORIENTATION RESULTS

Histograms showing orientation results for hothouse and plum tomatoes are shown in figures 8 and 9, respectively. No figure is shown for globe tomatoes as results concerning use of tracks to orient globe tomatoes were ambiguous. For hothouse tomatoes, data from the five tomatoes that weighed

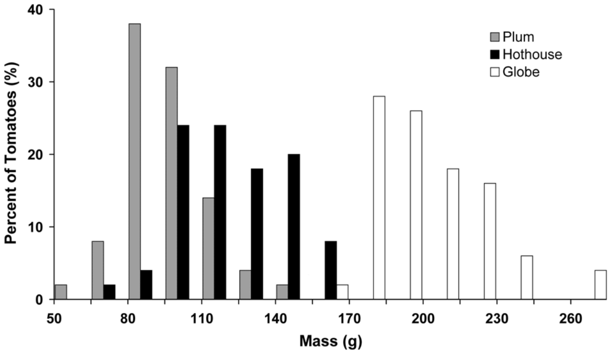

Figure 5. Mass distribution of plum, hothouse, and globe tomatoes (*n* = 50 each). Mass values were binned at intervals of 15 g starting at 50 g, and each bin encompasses tomatoes with masses greater than the next lower bin value and less than or equal to the bin value.

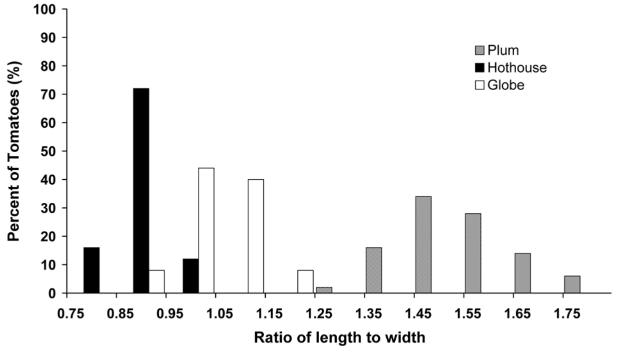

Figure 6. Distributions of ratios of length to width of plum, hothouse, and globe tomatoes. Ratios were binned at intervals of 0.1 starting at 0.75, and each bin encompasses tomatoes with a ratio greater than the next lower bin value and less than or equal to the bin value.

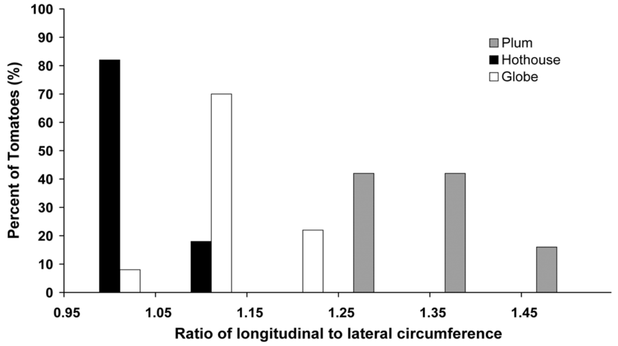

Figure 7. Distributions of ratios of longitudinal to lateral circumference of plum, hothouse, and globe tomatoes. Ratios were binned at intervals of 0.1 starting at 0.95, and each bin encompasses tomatoes with a ratio greater than the next lower bin value and less than or equal to the bin value.

less than 84.5 g were excluded from analyses as these tomatoes were small, spherical, and often got caught between the rails. Single-pass orientation rates averaged over 87% for the lower third of the track. Three-pass orientation rates were 100% from 90 through 250 cm of travel. For plum tomatoes, average single-pass orientation rates were about 88% from 150 through 270 cm of travel. Three-pass orientation rates were 100% from 110 cm of travel to the end of the track.

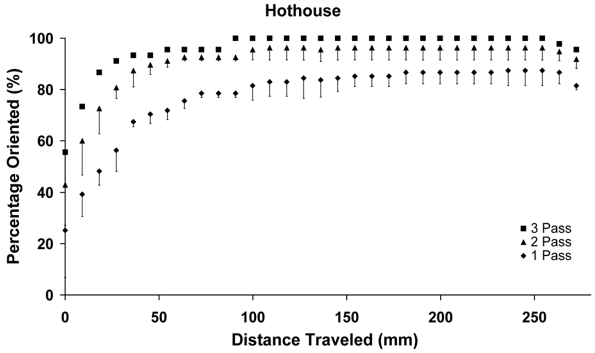

Figure 8. Percentage of hothouse tomatoes oriented as a function of horizontal distance traveled and number of passes down the track. Data are binned for 20-pixel (9.1 cm) intervals.

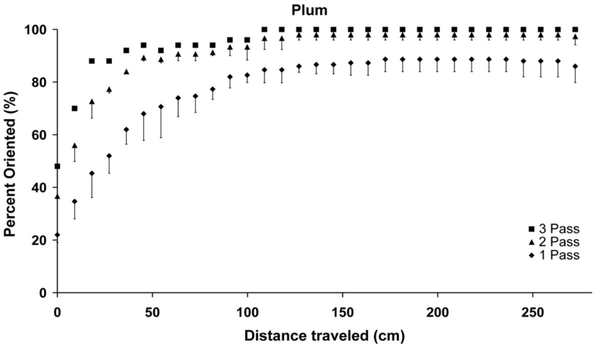

Figure 9. Percentage of plum tomatoes oriented as a function of horizontal distance traveled and number of passes down the track. Data are binned for 20-pixel (9.1 cm) intervals.

Orientation of globe tomatoes was more problematic. Single-pass orientation rates were only about 50% for a 30 cm region near the center of the track. With three passes, orientation rates exceeded 90% for this same region. At the optimal location of about 120 cm, 47 of the 50 tomatoes were oriented after three passes. There were no consistent characteristics that explained the results for the three tomatoes that failed to orient. Sectioning of randomly selected globe tomatoes demonstrated little evidence of a density distribution relative to the stem/blossom axis that might facilitate orientation due to inertial effects (fig. 10). More specifically, there is no evidence of any radial symmetry of septa or voids around the stem/blossom axis that might provide a density gradient favoring rotation around this axis.

DISCUSSION

COMPARING COMMERCIAL POTENTIAL OF ORIENTING APPLES AND TOMATOES

The benefits of orienting apples for imaging have been clearly elucidated (Lefcourt et al., 2009; Reese et al., 2009); however, there has been little discussion of this issue relative to tomatoes. The use of machine vision for sorting apples is well established, and the mechanisms used for sorting are fairly uniform throughout industry. For sorting, apples are conveyed in individual cups, and imaging is accomplished by passing the cups underneath an imaging system. Apples are sorted by using image and other sensory data to activate sole-

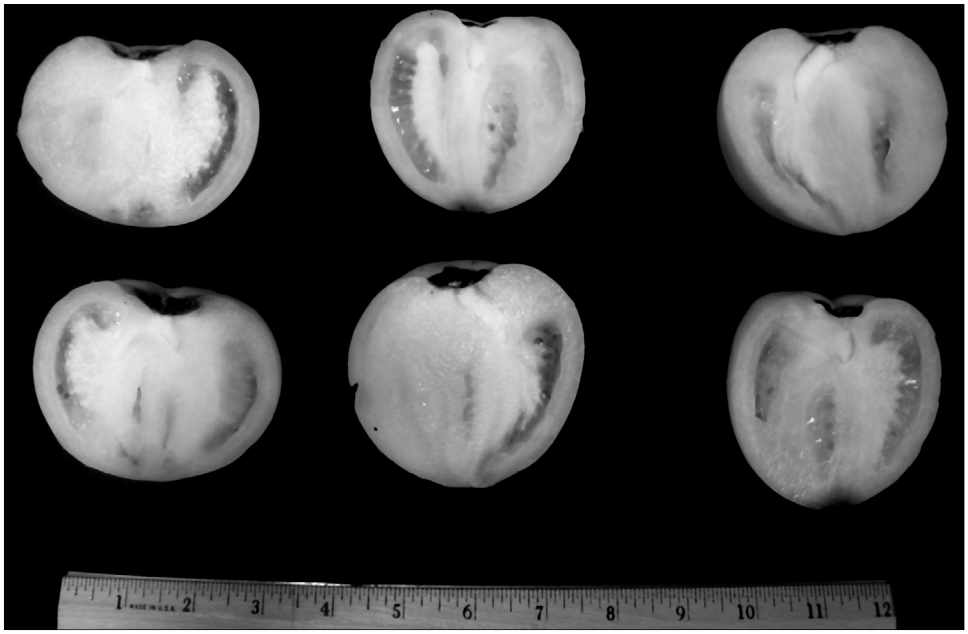

Figure 10. Cross sections of randomly selected globe tomatoes used in this study.

noids at appropriate times so that the apples are moved into selected sorting lanes. In contrast, the use of machine vision to sort tomatoes is not well established, and sorting is still often done by hand. Furthermore, there is no universally accepted transport mechanism for automated sorting systems; both single-cup (Consumers Produce, 2009) and belt conveyer (Odenberg, 2009) systems are commercially available.

Regardless of commodity, the concept of using tracks to transport "spherical" produce is novel and presents many potential advantages, including very low capital costs and essentially no maintenance costs. For the apple processing industry, the developmental costs of a track-based sorting system are probably prohibitive given that existing commercial sorting systems met current user needs. However, if the ability to sort apples for signs of fecal contamination becomes an important food safety issue, it will be advantageous to orient apples during processing so that the stem and calyx regions can be clearly and reliably imaged. The ability to detect fecal contamination of apples has been demonstrated (Kim et al., 2002; Lefcourt et al., 2003, 2005), as has the advantage of orienting apples for imaging so that cameras can easily see inside the concave stem and calyx regions (Reese et al., 2009). As automated sorting of tomatoes is less established, there is more leeway for the consideration of using tracks for transport during processing. The ability to orient tomatoes for imaging can improve the accuracy of size estimates derived from image analyses (Moreda et al., 2007, 2009). Orienting tomatoes for imaging may also have advantages in terms of food safety. Current recommendations state that "whole tomatoes should be free of obvious signs of filth, and skin damage such as punctures, cuts or breaks" (North American Tomato Trade Work Group, 2008). The stem is a particular area of concern. Tests show that the stem is particularly susceptible to bacterial infiltration when tomatoes were immersed (Bartz and Showalter, 1981) or when stems were in contact with soil (Guo et al., 2002). In addition to studies regarding the use of imaging to determine tomato size, some work has been done concerning development of imaging techniques for addressing color, ripeness, and quality issues (Jahns et al., 2001; Polder et al., 2002). The cited studies imaged the tomatoes in an oriented position with the stem or blossom end facing the camera. Thus, a distinct obstacle to implementation of imaging systems based on these results in a commercial setting is the need for a cost-effective, reliable method for appropriately orienting tomatoes for imaging.

MODIFICATION OF AUTOMATED DETECTION SOFTWARE

The major problems with using the software developed to automatically detect the stem and calyx regions in apples (Lefcourt et al., 2008) to detect similar regions in tomatoes are the difficulty of reliably detecting the blossom ends and locating the center of either the stem or blossom ends. A decision was made not to attempt to develop automatic detection software for tomatoes, as development would require significant effort, would be biased by the use of markers to highlight the stem and blossom ends, and the algorithm would probably not be useful in a commercial system. In a commercial setting, it is likely that hyperspectral or monochrome images at multiple wavelengths would be acquired, as opposed to the gray-scale images acquired in this study. By selecting appropriate wavelengths for imaging, it should be possible to enhance differences between the structures of interest and the normal tomato surface, which would facilitate development of algorithms to detect the stem and blossom ends. In any case, validation of a detection algorithm would still require that videos be examined on a frame-by-frame basis. Given the need for this intensive scrutiny of the videos, it was decided that it would be easier just to modify the software to allow users to use a mouse to identify the location of the center of the stem or blossom ends in videos.

The criteria for classifying whether an object was oriented were also changed for this study. The automated software used the distance from the center of the apple to the center of the stem or calyx in an image to determine whether an apple was oriented in a particular frame. In this study, this criterion was simplified to require only that the stem or blossoms end was fully visible in the frame image. It was found that if a tomato was oriented in three consecutive frames, then the tomato was rotating around the stem and blossoms end axis. In any case, the degree of orientation is not as critical for tomatoes as it is for apples, as there is little or no indentation of stem and blossom ends in tomatoes.

MODIFICATION OF TRACK DESIGN

It was initially assumed that a track used in a prior experiment to orient apples would also work well with tomatoes. This proved to be a poor assumption. In a full set of test trials, plum tomatoes flew off the track or rolled end over end. Orientation rates for globe tomatoes were poor, and results for replicate trials were rarely consistent. Hothouse tomatoes often got caught between the rails. As orientation problems appeared to be cultivar dependent, it was decided that unique tracks would be developed for each cultivar.

Prior observations suggested that two primary factors should be considered when trying to improve rates of successful orientation: track compliance and object shape. An example of the importance of compliance can be seen when results from two prior studies concerning orienting apples are compared. In a more recent study (Lefcourt et al., 2009), a shorter and hence stiffer track was used, and single-pass orientation rates were reduced in comparison to a prior study where a longer track was used (Narayanan et al., 2008b). For this study, knowledge of the dynamics of the orientation process as well as an empirical understanding of factors that affect the orientation process were used to design test tracks for the three tomato cultivars.

The dynamics of a rolling object with two points of contact are difficult to model. A first pass at trying to model such dynamics is to look at rotation of a free body, i.e., a rotating body with no point of contact. For a body with an axis of axial symmetry, rotation is stable only around this axis (Narayanan et al., 2008a). This situation corresponds to rotation around the stem/calyx axis in apples or the stem/blossoms end axis in tomatoes. However, rotation around an axis perpendicular to this axis can be locally stable, i.e., stable unless the rotation is perturbed. This situation corresponds to end-over-end rotation of apples or tomatoes. Problems with this model arise primarily because of the shapes of objects and the two potential points of contact during rotation and travel down the tracks. Factors to consider regarding shape include size, effective radius of the object at the two points of contact with the rails, and irregularities in shape. If objects are small relative to the distance between rails, the object can get stuck or fall between the rails. If an object is rotating around the axis of symmetry and the radii perpendicular to the plane of the rails at the two points of contact are different, then the object has to either "skip" along the rail where the radius is smaller, "slip" along the rail where the radius is larger, or some combination thereof. In this regard, it is often observed that apples rolling down test tracks lose contact with one rail for a period of time. Irregular shapes can cause a problem when an irregularity contacts a rail. Both unequal radii and shape irregularities can generate forces tangential to the directions of rotation or travel. Generating tangential forces is not necessarily bad. In fact, such forces provide the impetus that allows objects to change their orientation as they travel down a track. The problem is that excessive forces can cause objects to permanently leave a track. To mitigate this problem, the compliance of a track can be increased so that excessive forces can be distributed over time. In addition, compliance in the tracks can allow small forces to be amplified by resonance to the point where the generated force is sufficient to move objects to an orientation where the rotation is about the axis of symmetry. Evidence of this resonance effect can be seen in the sinusoidal movement of a track as apples travel down a test track (Narayanan et al., 2008b).

The first problem addressed in designing new tracks was the effects of tomato shape. Small tomatoes and elongated tomatoes had a tendency to get stuck between the rails or to orient themselves so that the narrowest aspect of the tomatoes rolled between the rails. Two possible solutions were considered: reducing the distance between the rails, and adding obstacles such as a third rail between the two normal rails so that the tomatoes were lifted off one of the two normal rails if they were rolling end over end. Reducing the width between the rails can increase the tendency for objects to roll laterally off the track. This effect can be demonstrated by rolling an apple down a flat surface. Most apples will not roll in a straight line, but will tend to move to the left or right as rotational velocities increase. Increasing the compliance of the tracks can be accomplished in many ways. The flexibility of the rails can be increased, the distance between supports can be increased, compliance can be introduced or increased at the ends where the tracks are supported, or some combination thereof. Past efforts in this regard included use of more flexible rails and placing the end of the track on egg-crate foam (Lefcourt et al., 2009). In this study, spring supports were introduced at both ends of some tracks.

Problems with plum tomatoes were resolved through the use of very flexible polyvinyl chloride molding for the rails and by using only a single internal cross-brace. The internal and end cross-braces were constructed in a "U" shape using wooden molding. Orientation rates near the start of the track were improved by moving the interior brace nearer to the end of the track (fig. 3).

For globe tomatoes, the first modified track was wider and incorporated a third, center rail (track 2b in fig. 3). There was no improvement in orientation rate. The third rail was removed, and the track was narrowed to have a width of 51 mm, which is intermediate between the original track and the first modified track. To increase the flexibility of the track, the molding height was reduced to 39 mm and the number of crossbars was reduced to six. To avoid contact with the rolling tomatoes, the crossbars were moved so that they were attached below the bottom of the rails. Orientation rates were further improved by adding springs at both ends of the track (fig. 4).

The first track modified for hothouse tomatoes incorporated a center wooden rail with a triangular cross-section. Four rails segments were added spaced over the length of the track. A few variations in placement of the third rail were examined. The final track was similar to the first modified track except that the lower two center rails were replaced by duplicate sets of two angled rails.

TOMATO SHAPES AND THEORETICAL CONSIDERATIONS

Orientation methods based on object shape and gravity are generally optimized to deal with either squat or elongated shapes and, as a result, orientation attempts for the alternate shape can suffer. In contrast, theoretical considerations suggest that orientation of objects with either elongated or squat shapes can be accomplished using inertial effects (Narayanan et al., 2008a). The potential drawback of using inertial effects is the difficulty of orienting spherical objects, which have an infinite number of axes of symmetry. Orientation methods based on gravity also have problems dealing with spherical objects. Thus, on a theoretical basis, orientation methods based on inertial effects are more robust than methods based on shape and gravity. The tomato cultivars used in this study were selected with the objective that the shape characteristics of the three cultivars should match the characteristics of the three groups used to make theoretical predictions, which were elongated, spherical, and squat. Both the ratios of length to width (fig. 6) and longitudinal to lateral circumference (fig. 7) demonstrate that is appropriate to classify the groups of plum, globe, and hothouse tomatoes as elongated, spherical, and squat, respectively.

ORIENTATION RESULTS

Direct comparison of orientation results between apples and tomatoes is difficult. For the first study using apples (Narayanan et al., 2008b), the apples were loaded onto tracks in three fixed orientations, with the stem/calyx axis parallel, perpendicular, or at 45° to the track rails. Single-pass orientation rates were nearly 100% successful for the perpendicular and 45° loading conditions, and around 50% for the parallel loading condition. A second study was conducted using random loading to determine the prevalence and importance of the parallel loading condition (Lefcourt et al., 2009). Results demonstrated that problems associated with parallel loading conditions were real and not artifacts of the experimental design used in the first study. In the second study, single-pass orientation rates were about 80%, and three-pass rates were around 95%. Unfortunately, the track used in this second study was shorter and stiffer than the track used in the first study. It was hypothesized that decreased track compliance due to the use of a shorter track in the second study was responsible for the relative decrease in orientation rates. In this study, poor results in an initial test study resulted in the decision to attempt to optimize track designs, and the orientation rates using these optimized tracks were much improved when compare to those from the initial study. Using the optimized tracks, single-pass and three-pass rates for hothouse and plum tomatoes were around 90% and 100%, respectively. The three-pass orientation rate for globe tomatoes of around 90% compares favorably to the rate of around 50% for apples loaded using the parallel loading condition (Narayanan et al., 2008b). The relative advantage in regard to orienting spherical tomatoes is particularly noteworthy given that the spherical tomatoes in this study showed no evidence of an internal density distribution relative to the stem/blossoms end axis that would favor rotation around that axis. In contrast, the core of apples is less dense than normal apple tissue, and the resulting density distribution around the stem/calyx axis favors rotation around this axis. Density distribution is unlikely to be a major factor for orientation of elongated or squat objects, as the differences in inertial mass distributions relative to shape are much greater than any potential differences due to density distributions of tissue structures.

The ability to classify the plum, globe, and hothouse tomatoes as elongated, spherical, and squat, respectively, allowed theoretical predictions concerning shape and orientation to be tested. The results indicate that, as predicted by theory, it was easy to orient elongated and squat tomatoes, and difficult to orient spherical tomatoes. However, there is a downside to using different tracks to orient the different groups of tomatoes, i.e., tracks used in a commercial setting would have to be modified according to the intrinsic shape of the tomato cultivar being processed. Given the low cost of the tracks, selecting between a limited number of tracks might be feasible. Alternatively, it should be possible to design a track system in which the track features, such as compliance and width between rails, could be changed automatically as appropriate. Compliance could be adjusted by changing the spring loading at the end supports, and width could be adjusted by moving one rail. Obstacles, such as a third rail, could be brought in automatically as needed. An additional advantage of using an adjustable rail system is that a single sorting system could be designed for use with a variety of different commodities.

CONCLUSION

Results demonstrate that the orientation process based on inertial properties previously demonstrated to work for apples will also work for tomatoes. Furthermore, the shape characteristics of the tested plum, globe, and hothouse tomatoes allowed these groups to be classified as elongated, spherical, and squat, respectively. These shape characteristics and resulting orientation rates allowed confirmation of the theoretical prediction that it would be easy to orient elongated and squat objects based on inertial effects, and that it would be more difficult to orient spherical objects. However, even for the globe tomatoes, which tended to be "perfectly" spherical and which had a uniform internal density distribution, three-pass orientation rates approached 90%. Results of this study indicate that rolling quasi-spherical produce down tracks consisting of two parallel rails is a commercially viable method for orienting such produce for imaging.

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