IFAS Citrus Initiative
Annual Research and Extension Progress Report FY2011-12

Title:
Machine Enhancement for Citrus Mechanical Harvesting Equipment

Investigator(s):
Reza Ehsani

Objective(s) Pursued:
***Objective 1:* Improve engineering solutions to reduce debris in mechanically harvested fruit**

Detailed Accomplishments in 2011-2012:
Task 1- *To make improvements to the pull-behind debris removal platform modified during 2010-2011.*
Further improvements were made to the debris removal machine that was redeveloped and modified during 2010-11. Enhancements were made to improve the efficiency of the operation, such as: (i) Added output conveyor guard brackets (Fig. 1a) for quicker installation. (ii) Installed a raised solar panel mount (Fig. 1b) in order to capture more direct sunlight. (iii) Added a vertical hopper gate (Fig. 1c) in order to better regulate fruit flow. (iv) Added a permanent sensor box (Fig. 1d) to improve set-up time. (v) Added an output conveyor positioning cylinder (Fig. 1e) in order to ease conveyor setup movement, especially with various terrain inclination angle conditions. (vi) Added a debris conveyor and catch pan (Fig. 1f) in order to increase debris collection and test evaluation efficiencies.

Task 2- *To conduct field experiments, in order to evaluate the pull-behind debris removal machine's performance with respect to both fruit recovery and harvested load debris.*
Field data collection began December 8th at the Lykes Fort Mach orchard in Lake Wales. Thirteen tests were performed on Parson Brown oranges which were machine-harvested using the Oxbo 3210 and subsequently picked up from the ground by hand. Nine tests were performed on Hamlin oranges on January 13th to 26th in the same manner. Nine more tests on the Midsweet citrus variety were performed on January 18th, however in this test the loads were entirely picked off the trees by hand. Eight additional Valencia tests (May 1 and 15th) were performed. Those tests, along with those from the 2011 season, add up to a total of 21 Valencia tests which was harvested using the Oxbo 3220. Since some of the mechanical harvesting tests were performed by the Oxbo 3210, emphasis was given toward categorizing the combination of leaves and wood (including stems, twigs and dead wood), bad fruit (immature, damaged and rotten) and sand. Sand is an issue when fruit is harvested and then picked up at a later period or date. Mean debris percentages were determined from each category, and then the overall potential total mean percentage of debris for each load was established. Machine-harvested loads produced up to approximately four-times more debris than hand-harvested loads, as shown in in Fig 3.

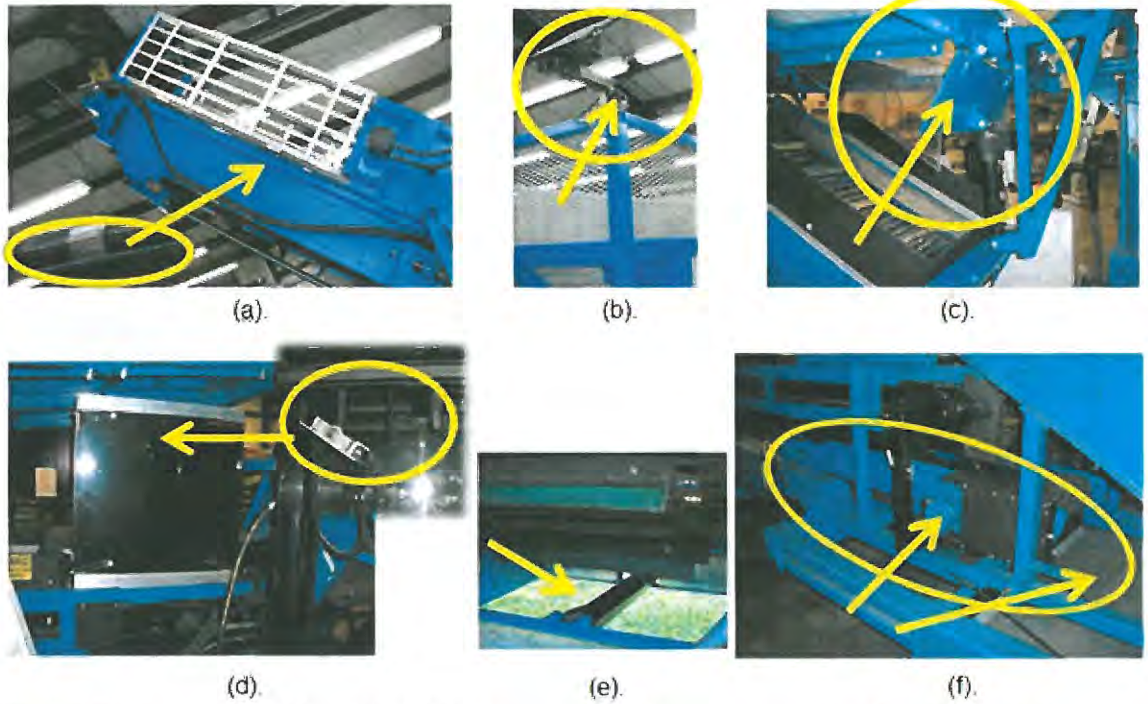


Fig. 1. Debris removal machine with added enhancements: (a) output conveyor bracket, (b) raised solar panel mount, (c) vertical hopper gate, (d) permanent sensor box, (e) output conveyor positioning cylinder, and (f) debris conveyor and catch pan.

The abscission compound was used on ten Valencia tests and on average, reduced the load debris by approximately 30 percent over the regular machine harvesting method (Fig. 3). The early May 2012 Valencia tests indicate an 82 (abscission) and 90 (non-abscission) percent total debris reduction, as compared to the 2011 tests value. Such a reduction could be due to variables as: 1) The winter months of 2011 endured a freeze period, which affected the trees. 2) There is less tree damage from the mechanical harvester when the tines are positioned within the canopy similar to the previous year's harvesting. 3) Increased fruit size. 4) Possible change in machine operator.

Key findings can be summarized as:

- Results confirmed that mechanical harvested fruit produces more debris compared to hand-harvested loads and this amount was quantified.
- There is a significant amount of variability in the amount and type of debris created by different types of mechanical harvesting machines. Factors such as: type of machine, harvest time during growing season, fruit variety, frost damage, operator skills, and previous history of being mechanically harvested could significantly change the amount of debris.
- While overall, the Oxbo 3220 created slightly less debris compared to the Oxbo 3210, the types of debris were different. The Oxbo 3220 debris contained larger size branches and dead wood compared to the Oxbo 3210 hand-picked load. The amount of leaves and sand was higher in the Oxbo 3210 hand-picked loads.

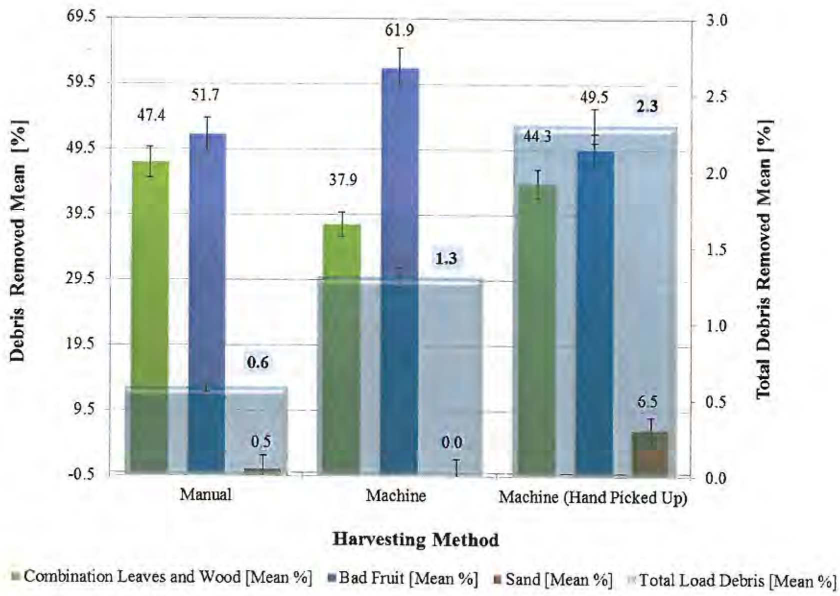


Fig. 2. Categorized and total debris removed from 46 test loads of four different citrus varieties (Parson Brown, Hamlin, Midsweet and Valencia) with a mean weight of 4060 lbs.

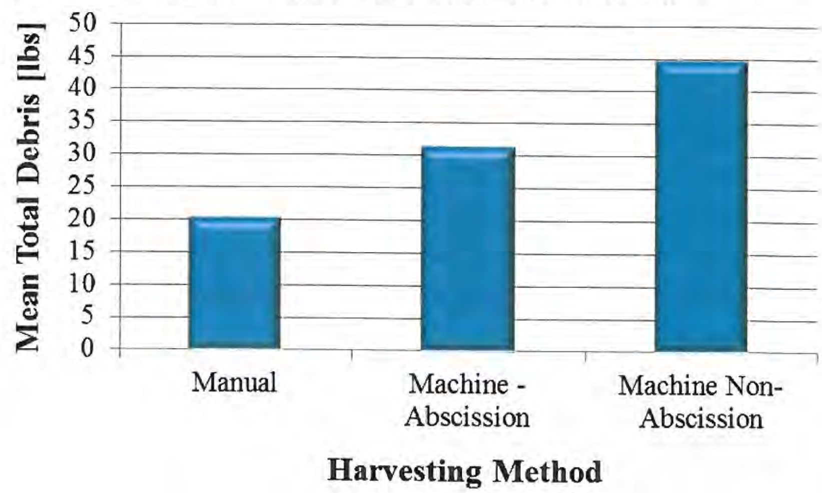


Fig. 3. Mean debris removed comparison between the harvesting methods, including the abscission compound, from 21 Valencia test loads with a mean weight of 2924 lbs.

Objective 2: Machine improvement and alternative design

TASK-1 *To develop and study a citrus catch-frame attachment for the pull-behind mechanical harvester in order to reduce the quantity of fruit dropping to the ground during harvesting and reduce the associated labor with fruit collection.*

The task was changed from developing a citrus catch-frame attachment as originally suggested to developing a fruit pick-up head for an Oxbo pick-up machine. The original and only Oxbo prototype pick-up machine is being modified and enhanced to increase fruit pick-up efficiencies (Fig 4a). A new system of collecting the fruit from the ground was developed. It consists of wheels made of flexible rubber flaps capable of adjusting to the contour of the ground in conjunction with a new platform (Fig 4b). The system is able to float on the ground surface as opposed to digging into and beneath the ground surface. The preliminary tests in grass, sand and the CREC orchard resulted in 100 percent fruit pickup at a maximum of 1 mph ground speed. Further tests enhancing windrow techniques and an allowance for swell areas are yet to be incorporated and tested.

(a) (b)

Fig. 4. a) Oxbo pick-up machine during original testing. b) Modified machine at CREC.

TASK-2- *To develop and study alternative harvesting technologies*

Mobile mechanical harvester component and evaluation test station

The donated MaQtec citrus harvesting machine was converted into a mobile mechanical harvester test station, as shown in Fig 5a. Most of the non-functional conveyors, elevators and shoots were removed (Fig 5b). The machine provides an adequate hydraulic power source and a rigid structure to mount and operate various components. The objective of the test station is to study and evaluate potential fruit removing devices, such as tine and air-induced systems in order to reduce tree damage and improve mechanical harvesting efficiencies. The test station provides a means to simulate component interaction within a given operating environment.

(a) (b)

Fig. 5 a) The MaQtec harvester 2011 before modification. b) The MaQtec harvester converted into a mobile mechanical harvester test station.

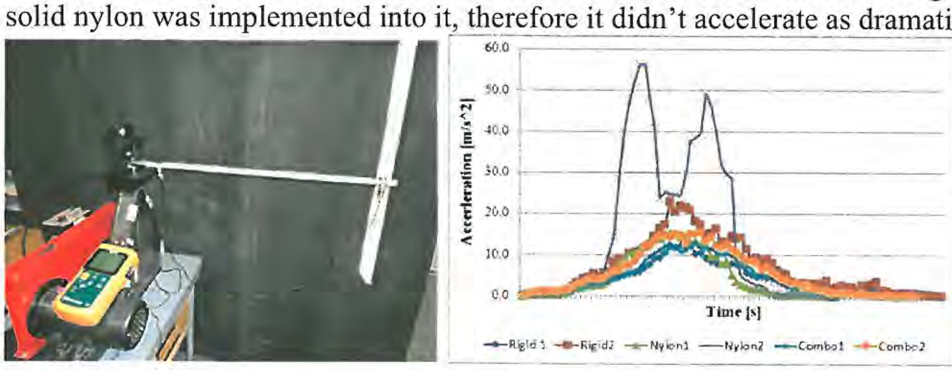
Presently, the test station contains a hydraulic-actuated pivoting tine rig and a branch-bending stress and deflection evaluation system (Fig 6). The pivoting tine rig incorporates an adjustable clamping device in order to study various material diameters.

Fig. 6: The research-based mechanical harvester component and evaluation test station with the present pivoting tine rig and a branch-bending stress and deflection evaluation system.

This system allows for real-time and full-scale tine material and related component development and evaluation. Most recent activities have been focused primarily on setting up the system, so no data has been produced. The present system involves a 1.63 OD, 0.65 wall thickness, 72 in. length 4130 DOM hardened steel tube from an Oxbo 3220 mechanical harvesting machine. The tube is secured at one end by an adjustable compression clamp in the pivoting tine rig, which helps avoid reduced tension stress. The setup simulates the cantilever beam principle for both theoretical purposes and actual mounting scenarios. The other end of the tube remains free to impact a nylon rod, which currently simulates a tree branch. The nylon has enough elasticity to aid with initial system set-up and the required instrumentation learning curves prior to using real tree branches.

Small tine test rig

A small test rig was also utilized to test and compare different tine materials Fig 7a. On the rig, a push rod moves up and down at a defined distance (stroke length approx. 1.5 in.) at various revolutions per minute (54, 141, 226 and 308 rpm). Three different tine tests were conducted. Tines were constructed from three different materials: rigid, nylon, and a combination of rigid and nylon. Results indicated the averaged percent difference between the fixed and free end acceleration (m/s^2) values were: Rigid 46%, nylon 73% and the combination materials was 18%. The nylon dynamic bending displacement (+/- 12 in.) from zero peaked at rpm values between 141 and 226. The material stabilized at values close to 308 rpm. Rigid materials offer greater stability, whereas more elasticity materials offer greater flexibility. The combination tine had more end weight, since the solid nylon was implemented into it, therefore it didn't accelerate as dramatically.



(a) (b)

Fig. 7 a) The small tine test rig with the rigid EMT tubing and attached accelerator sensors. b) Averaged acceleration values for three different tine materials at two different locations for each tine material.

Deflection and bending stress test rig

Theoretically, when a static force is applied to the free end of a cantilever beam the material properties define how far it deflects (in.) and how much bending stress (psi) it is subjected to. Table 1 indicates the typical material deflection and bending stress values for the following materials: Nylon rod (1.63 in. OD); steel and carbon fiber tubing (1.63 in. OD and 0.065 wall thickness); and wall steel square tubing (1.5 in. with a 0.1875 in.). All have lengths of 72 inches. These values help define material choices but additional criteria is needed to define what happens when materials are subjected to a dynamic load. The 1.5 in. square steel tubing was chosen to be incorporated into a test rig as the main impact push rod object, because it has the least deflection and bending stress value compared to the other materials at varying force values.

Table 1. Material deflection and bending stress calculated values at various static force increments. Material dimensions include: 1.63 in. OD Nylon rod; 1.63 in. OD and 0.065 in. wall thickness steel and carbon fiber tubing; 1.5 in. with a 0.1875 in. wall steel square tubing.

	Material Deflection [in]				Material Bending Stress [psi]			
Force [lbs.]	Nylon RD	Steel RD	Carbon fiber RD	Steel SQ	Nylon RD	Steel RD	Carbon fiber RD	Steel SQ
5	6.1	0.2	0.2	0.12	846.7	2993.6	2993.6	1763.4
10	12.1	0.4	0.5	0.25	1693.4	5987.2	5987.2	3526.8
50	59.8	2.1	2.4	1.25	8467.2	29936.1	29936.1	17633.8
100	119.7	4.2	4.7	2.5	16934.4	59872.2	59872.2	35267.6
500	598.4	21.2	23.5	12.5	84672.0	299361.0	299361	176338.2

A boom-style deflection and bending stress test rig was developed and incorporated onto the front fork end of a Terex telehandler machine in order to rise to varying tree canopy heights. The test rig incorporates an Avery Weigh-Tronix weigh bar with a static capacity of 7,500 lbs. Structural grade square tubing (2.5, 2.0 and 1.5 inch) with 0.1875 inch wall thicknesses was used for the telescoping boom feature, in order to reach various canopy depths. The frame has an adjustable inclination angle of up to 90 degrees, in order to adapt to various tree branch growth angles. Five Naval variety orange trees were randomly chosen at the CREC facility test orchard. The test rig was operated either perpendicularly (Fig. 8a) or at a 45-degree angle (Fig. 8b) within the canopy. The maximum branch bending stress force range was between 110.6 to 556.7 lbs, with branch diameters reaching 4 inches. The branch deflection distance ranged from 12 to 56 inches, depending on the branch length and push rod position placement. The push rod was placed within the canopy to obtain the bending stress force. The force applied to various points on the rod was recorded. General observations indicate a rod placed perpendicular to the canopy will be subject to greater bending stresses. For both the tree and push rod, if the bending stress exceeds the materials yield strength it will be permanently deformed and not return to its original shape, which could lead to breakage.

Fig. 8 a)Deflection and bending stress test rig mounted on the Terex telehandler with a perpendicular canopy placement. b) The test rig with at a 45-degree inclination angle.

Air induced systems

The concept of using high velocity air for shaking trees (air shaking) in combination with abscission compound has shown in the past some potential for fruit removal with little damage to the trees. A 90,000 cfm conical scan air shaker system (Fig 9b) that was available at the CREC was restored and its performance was compared to a smaller 1,600 cfm Billy Goat Force II blower (Fig 9a).

Field tests were conducted at different air volumes and wind velocities were measured at different locations around the canopy. Both units were used to determine throughput canopy air flow at the CREC experiment orchard, Lake Alfred Florida. The amount of fruit removal and tree damage were measured. The Billy Goat air velocity (mph) was reduced as much as 70 - 90 percent just past the first outer canopy layer. The turbulence caused by the actuating valve helped the throughput air flow, but the machine's volume capacity proved too small to be very effective. The machine's air volume was good at close proximities and at concentrated durations. It's noted that none of the fruit was removed and no branches were damaged. The conical scan air shaker had a higher air volume, which by itself produced notable wind velocities similar to tornado or hurricane conditions. As the engine's rpm increased the inlet air suction increased by 49%, the blowers output increased by 30% and the overall canopy throughput air velocity increased by 42%. More of the tree's fruit was removed at the higher velocities and the canopy itself was shaking with limb displacement swaying reaching 4 and 5 ft. Some limbs were damaged and some were broken due to the concentrated turbulent shaking. This concept will be effective only with abscission compounds and will be incorporated in the future design if abscission compounds become commercially available.

(a) (b)

Fig 9. a) Billy Goat blower, b) Conical scan air shaker.

Task 3- To study mechanical harvesting machine fruit-removal systems that can Enhance production efforts.

Fruit removal efficiency and tree damage are dependent on the amount of energy transferred to the tree branches. This energy is generated when the tines shake the canopy to remove the fruits. The Oxbo 3210/3220 slider crank mechanism in the canopy shaker harvester gives reciprocation motion to the hub-tine assembly which in turn shakes the tree canopy for fruit removal. A mathematical model was developed to predict acceleration at the end of tines without considering the inertia effects of component and friction(Fig 10). The machine enhancement objectives can be achieved by modifying the shaking tine configuration or hub and tine assembly configuration.

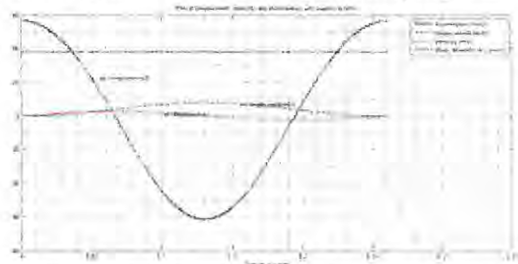


Fig10- variation of acceleration, velocity and displacement of tine with respect to time.

Canopy shaking tines are the main components of fruit removal systems on mechanical harvesting machines. Tines directly come in contact with the tree canopy and transfer vibrational energy to the tree which results in fruit removal. The goal of this task was to study alternative designs and enhance the performance of existing fruit removal systems used on the Oxbo canopy shaker. The following tine modification options have been proposed to achieve the desired goal.

<u>Option 1: Changing tine cross-section</u>

The current tines used on Oxbo canopy shakers consist of a circular tube with a 1.625 inch outside diameter with a 0.0625 inch wall thickness. The goal was to select the best cross-section which can increase fruit removal by transferring maximum vibrational energy to the tree canopy without significant damage to the tree canopy. It was found that increasing axial rigidity or stiffness increases the fruit removal and decreasing flexural rigidity or stiffness decreases the tree damage. The different cross-section dimensions have been studied to achieve desired objectives. The parameters of the cross-sections were optimized using a gradient-based constrained optimization algorithm. The tine with a rectangular cross-section provided the best results (1.85" x0.75"and 0.125(tickness)). However, further analysis must be performed before finally incorporating this design change into the current machine.

<u>Option 2: Composite tines</u>

The different composite tines were studied to minimize tree damage while keeping fruit removal as high as possible. The composite tines are made of different materials (nylon rod and steel pipe) and have cross-sections along the length of the tines. The various designs were optimized to reduce the overall cost of manufacturing. Some composite designs were optimized to meet the objectives of maximum fruit removal and minimum tree damage. However, further analysis and validation is required before incorporating them on the machine. Figure 11 shows a new design for a hub and tine assembly with deflectable tines that could potentially minimize tree damage.

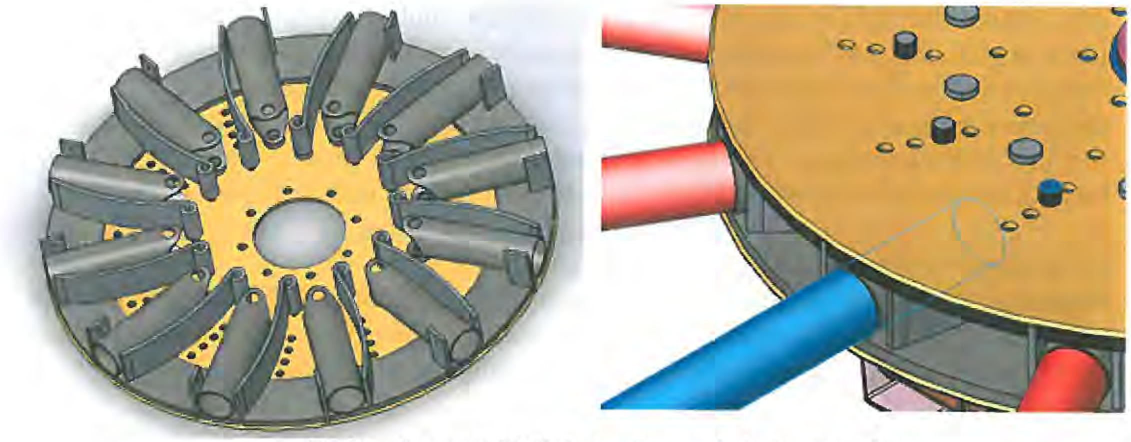


Fig 11. Proposed CAD design for new hub-tine assembly

Task 4- To enhance the functionality of tine control system for canopy shaker

The second version of tine control system was developed and a new enhanced feature was added to increase the functionality of the tine control system. The number of ultrasonic sensors used for canopy detection increased from two to four to cover a larger area of the tree canopy and to better estimate the canopy size and shape. The mast holding the sensors was also redesigned to facilitate the adjustment of the angles of the ultrasonic sensors with respect to the tree canopy. The new mast was made of extruded aluminum and sensors were installed on hinges so that their angles toward the tree canopy could be easily adjusted. Based on the knowledge learned from last year's work, a new controller system was designed and developed. All important variables which were used for the automated control system could now be changed directly using the interactive user friendly software, thus, reprogramming the firmware is not needed when changing a control parameter. Different algorithms could be tested directly and activated by running the algorithm using the terminal services. The algorithm could also be configured to run on start up. This means that the driver did not need to connect the controller to the laptop every time he wanted to use the automated tine control system. Calibrated values for the updated variables, e.g., forward speed, canopy thickness, etc. could be stored even when the controller was powered off. The algorithm used in the new control system was also changed. In this algorithm, the ultrasonic sensors were installed perpendicular to the tree canopies. On the other hand, another algorithm was also tested in which the angle of the ultrasonic sensors toward the tree canopy was determined based on the row spacing, the canopy thickness and the time it took for the tines to move from their current position to their desired position. A delay was computed for the tines when they were moving forward based on the forward speed of the tractor and the canopy thickness.

<u>Areas where progress exceeded expectations</u>:

Objective 1: The debris removal machine enhancements decreased set-up time and reduced the number of people needed to perform the debris collection part of the operation. The continuous flow from the debris conveyor made it safer and easier to gather the debris, because it is primarily concentrated it to one central area, versus the previous stationary collection sheet method. Data was produced from two different test

sites, which allowed for four different citrus varieties and two different machine harvesting methods to be analyzed. This diversity of testing provided an opportunity to further examine the experimental test machines performance efficiencies.
Objective 2, *Task 1:* Since the preliminary pick-up tests were successful at picking up all the fruit, this allows future testing to be done at faster travel speeds. Further testing is required to provide support data and machine performance characteristics.

Areas where progress didn't meet expectations:
Objective 2, *Task 1:* The machine operator must maintain operating the machine in the center of the rows, because sand dust reduces visibility; therefore, it is not advantageous for the operator to perform multiple tasks, i.e. raking the fruit and picking it up simultaneously.
Objective 2, *Task 2&3:* Due to multiple machine maintenance requirements, there wasn't enough time to do more tests and progress was less than expected.
Objective 2, *Task 4*: The number of field tests was less than expected. We accomplished only two field tests on the system. More field tests are needed to better evaluate the system performance.

Next steps:
Objective 1, *Task 1&2*: This study was able to quantify and compare the type and amount of trash between mechanically-harvested and manually-harvested fruit loads. The debris removal machine has demonstrated that the concept is working and it is possible to clean the harvested load in the field. A provisional patent has been issued for the trash removal mechanisms used in the trash removal machine and the commercial version of this machine can be built. What was learned during the course of this study will be incorporated into systems and mechanisms for debris removal in future machine enhancement and improvement projects.
Objective 2, *Task 1:* Further improvements on the head for the pick-up machine will be made and its performance will be evaluated under different field conditions.
Objective 2, *Task 2*: The test bench developed during this year's study will be used to test different tine materials and build the design concepts that were developed in this study.
Objective 2, *Task 3*: The proposed modification for the tine and hub assembly need to be built and tested.
Objective 2, *Task 4*: The automated tine control will be installed on an Oxbo 3220 and the performance of it will be evaluated and compared with the existing manual system.

Impact of accomplishments towards overall goals of funding:
The fruit removal system is one of the main components of mechanical harvesting machines. Improving the fruit removal system through a combination of theoretical and applied research can significantly improve the performance of existing and future mechanical harvesting machines. The results from this current research project in combination with other research projects such as the tree mapping system and the tine control system will allow development of a more precise fruit removal system with better fruit removal efficiency and reduced tree damage.

Presentations associated with 2011-12 efforts:

1. Valentine, A., R. Ehsani. 2011. In-field debris removal and fruit quantity and quality sensing in citrus. International Citrus & Beverage Conference, Clearwater Beach, FL, September 15.
2. Ehsani, R. 2011. Mechanical harvesting and abscission: machine enhancement plan of work 2011-12, Citrus Harvesting Research Advisory Council meeting, Bartow, FL.
3. Ehsani, R. 2012. Alternative design for fruit removal systems, Citrus Harvesting Research Advisory Council meeting, Bartow, FL. Feb. 21, 2012.
4. Ehsani, R. Citrus mechanical harvesting, University of Ankara, Turkey. March 12, 2012.
5. Ehsani, R. 2012.Mechanical harvesting for fruit trees, Namik Kemal University, Turkey. March 14, 2012.
6. Valentine, A., R. Ehsani, and W.S. Lee. 2012. Keeping the debris out of mechanically harvested loads. International Symposium on Mechanical Harvesting & Handling Systems of Fruits and Nuts, Lake Alfred, FL, April 3.

Publications from 2011-12 efforts:

1. Khosro Anjom, F. 2011. An automated tine control system for tractor drawn citrus canopy shakers. MS thesis. Gainesville, Florida: University of Florida, Agricultural and Biological Engineering Department.
2. Valentine, A., R. Ehsani, and W.S. Lee. 2011. Keeping the debris out of mechanically harvested loads. Proceedings of International Symposium on Mechanical Harvesting & Handling Systems of Fruits and Nuts, Lake Alfred, FL, April 3.
3. Shin, J. S., A., W. S. Lee, and R. Ehsani. 2011. Machine vision based citrus mass estimation during post-harvesting using supervised machine learning algorithms. Proceedings of International Symposium on Mechanical Harvesting & Handling Systems of Fruits and Nuts, Lake Alfred, FL, April 3.
4. Khosro Anjom, F., J. M. Maja, R. Ehsani, and W. S. Lee. 2012. An automated tine control system for tractor drawn citrus canopy shakers. ASABE Annual International Meeting, Dallas, TX, July 29-August 1.
5. Shamshiri, R., R. Ehsani and F. Roka. Determining field efficiency and field machine index for a citrus canopy shaker from raw yield data. 18 pages. Journal of Applied Engineering in Agriculture. (In review)

Patents

Ehsani R., A. Valentine, and W. S. Lee. 2011. Systems and methods for plant material removal for harvested crops. Provisional Patent. EFSID:10955492. Application Number: 61534998.

IFAS Citrus Initiative
Annual Research and Extension Progress Report FY2011-12

Title: Postharvest Citrus Mass and Size Estimation using Machine Vision

Investigator(s): Wonsuk Lee, Reza Ehsani
Graduate Research Assistant: Junsu Shin

Objective(s) Pursued:

The objective of this research was to develop a real-time machine vision system for citrus mass and size estimation during postharvesting operation in the citrus debris cleaning machine. To achieve fruit detection, supervised learning algorithm was developed, and a modified version of the watershed algorithm was proposed. The fruit detection algorithms were developed such that they could form a basis for developing an advanced citrus yield mapping system in future research.

Detailed Accomplishments in FY2011-12:

Hardware system

The machine vision hardware system for the yield estimation consists of a CCD color camera (Bobcat GigE VGA, Imperx Inc., Boca Raton, FL), two of white Exolights (MetaWhite™, Metaphase Technologies Inc., Bensalem, PA), an incremental encoder, and a data acquisition card (DAQCard-6036E, National Instruments, Austin, TX). A camera with high frame rates (206 fps) feature has been chosen for the acquisition of high quality images. For synchronization considering the speed of conveyor belt, an incremental encoder was installed on the rotating axis of the conveyor.

During the late harvesting experiments on May 2, May 19, May 31, and June 14 in 2011 at the Lykes grove in Fort Basinger, the machine vision system acquired images of citrus fruit moving over the conveyor belt of the de-trasher in the cleaning machine. Since the vision system was located at the end of the de-trasher, the citrus debris was filtered by the de-trasher and was most unlikely included in the images captured by the system.

Software design and algorithms

An algorithm to estimate citrus mass based on machine vision was designed including image rectification, image segmentation based on logistic regression model, morphological operations, highly saturated area recovering (HSAR) and mass calibration algorithms. The block diagram representing the flow of the image processing algorithm is shown in Fig. 1.

The process of camera calibration has been completed to get a model of the camera's geometry and a distortion model of the lens. Given the camera geometry and lens distortion model, the images were rectified.

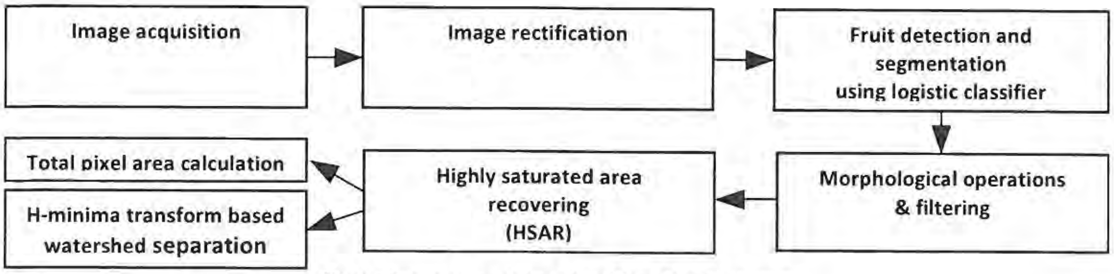


Fig. 1 - Image processing algorithm block diagram.

Pixel classification using logistic regression model

Classifying pixels into fruit or non-fruit is regarded as the binary classification problem. For the binary classification, logistic regression model is utilized. Logistic regression is quick to train and easy to implement. In addition, the model runs fast, so it is suitable for real-time processing. The outcome of this pixel classification is in the form of a binary image. The value zero (0) indicates a black pixel, and the value one (1) represents a white pixel in the binary output image. The white pixel region denotes where fruit resides in an image, but the black pixel area denotes background (non-fruit). In order to find distinctive feature vectors for the classification, the training images were converted from red, green, and blue (RGB) color space to various types of color spaces. The histogram analysis was performed in each color space. Fruit and non-fruit pixels occupy separate places with little overlapping in the histogram of hue (H), saturation (S), chrominance in blue (Cb) and chrominance in red (Cr) color components. Hence, these four color components were chosen as the feature vector.

Highly saturated area recovering (HSAR)

Some part of the fruit image and the background (non-fruit) image were highly saturated due to the light emitted from the lamps. The highly saturated areas may cause an error in the classification process, and hence they were excluded from the training sample for the logistic regression model. This means that the classification model does not identify the very bright areas on fruit in an image as fruit. Therefore, a highly saturated area recovering (HSAR) algorithm was developed to detect and recover highly saturated areas surrounded only by fruit pixels. The steps involved in the HSAR algorithm were:

1) Find all highly saturated areas by thresholding operation.
2) Extract pixels in circumference around the areas found in step (1) by the combination of dilation and logical AND operation.
3) Look up the extracted pixels and see if they are part of fruit using the fruit color.
4) If they are fruit pixels, add the identified areas to the classification result by logical OR operation.

Fruit separation using H-minima transform based watershed transform

In order to count the number of fruit and to estimate the fruit diameter, neighboring fruit which joined together in the output binary image need to be separated. To separate the touching fruit into individual fruits, watershed transform was conducted on the inverse distance transform of the complement of the output binary images. However, it should be noted that the watershed separation yields over-segmentation because every local minimum forms its own catchment basin which comprises one segmented area after the transform. To minimize the over-segmentation effect, local minima that are too shallow are eliminated using H-minima transform. The H-minima transform is a powerful tool to suppress local minima whose depth is lower than a given threshold.

Mass calibration and estimation
While conducting each of the field experiments, a total of 40 fruit samples with varying sizes and masses were taken in order to calibrate the pixel area of fruit with respect to actual mass. The pixel area for each fruit sample was found out from the binary images obtained from manual cropping using an image editing software. The mass of the individual fruit sample was measured using a weighing scale. A regression analysis was conducted to find a relationship between pixel area and actual mass. A linear model was assumed in the analysis. Hence, the model has the form of Eq.1.

$$Estimated\ mass\,(\mathrm{kg}) = p_1 \times pixel\ area + p_2 \tag{1}$$

Table 1 lists the results of regression analysis on the three mass calibration sets, which include the constants p_1 and p_2 defined in Eq. 1.

Table 1 - Results of regression analysis on the three mass calibration sets.

Experiment number	Error sum of squares (SSE, kg)	Coefficient of determination (R^2)	Root mean square error (kg)	p_1	p_2
1	0.0055	0.982	0.0121	0.0000636	-0.0892
2	0.0322	0.924	0.0291	0.0000686	-0.0273
3	0.0303	0.929	0.0282	0.0000718	-0.0659

Results
The main finding of this work is the development of an image processing algorithm to perform the detection of citrus fruit in an image to estimate fruit mass. Pixel area corresponding to fruit was computed based on the binary image obtained from the image processing algorithm. The core part of the image processing algorithm is the logistic regression model based image segmentation, designed for classifying pixels as fruit or non-fruit. Figure 2 summarizes the whole process for the fruit identification.

The image processing algorithm was applied to all images acquired from the field experiments, and binary images were generated. Then, the entire pixel area corresponding to citrus fruit in the experiment set was computed. The sum of pixel area was then mapped to estimated fruit mass using Eq. 1. Table 2 summarizes the estimation results. Regression analysis was conducted on the estimated fruit mass with respect to the measured mass obtained from the entire experiment sets. The highest R^2 between the measured fruit mass and the estimated fruit mass was 0.945. A root mean square error (*RMSE*) was 116.2 kg.

After only fruit regions were extracted from the image processing algorithm, the watershed transform was applied to separate joined fruit into individual fruits. The acquisition of individual fruit images enabled the number of fruit to be counted and the diameter of fruit to be estimated. The watershed transformation generated incorrect separation which led to over-segmentation since the regional minima were utilized directly for separating the touching fruit. The excessive over-segmentation in the watershed separation was prevented using H-minima transform. The appropriate constant h value was chosen empirically for the best segmentation. Figure 3 shows the results of the watershed separation with and without H-minima transform. Table 3 summarizes the potential distribution of the fruit size and counting. As shown in the table, a majority of fruit had diameter between 6 cm and 8 cm. The average fruit size ranged from 6.4 cm to 7.0 cm.

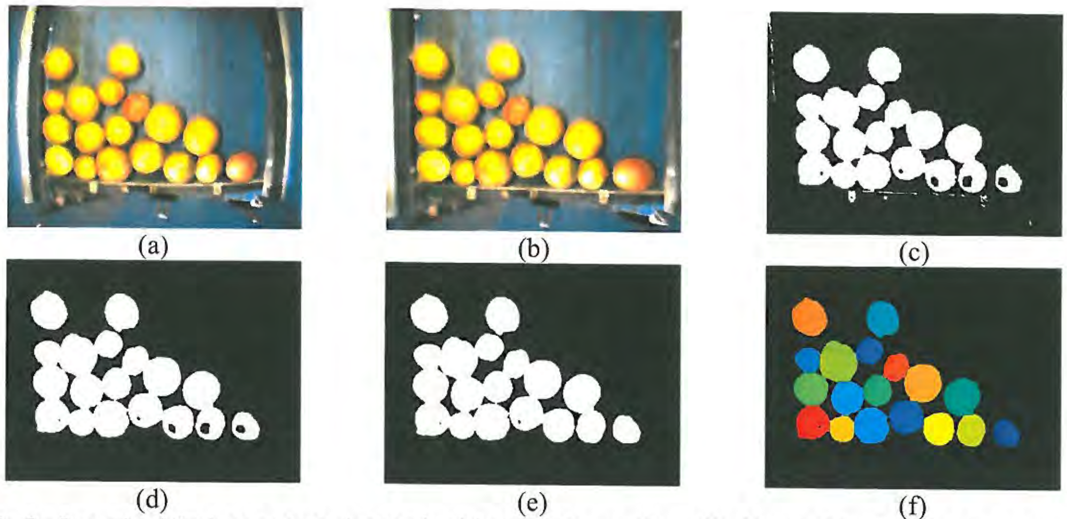


Fig. 2 – Example of the image processing results: (a) original image, (b) rectified image, (c) segmented image using logistic regression model, (d) after performing morphological operations and filtering, (e) after HSAR, and (f) H-minima transform based watershed separation.

Table 2 - Summary of the field experiment results.

	Set number	Measured fruit mass (kg)	Fruit pixel area (pixels)	Estimated fruit mass (kg)	Measured mass – Estimated mass (kg)	*Error (%)
1st experiment	1	1,721.4	25,105,593	1,597.6	123.8	7.2
	2	587.4	10,317,474	656.5	-69.1	-11.8
	3	739.4	12,053,362	767.0	-27.6	-3.7
	4	1,984.5	29,128,644	1,853.7	130.8	6.6
2nd experiment	1	1,492.3	22,631,009	1,552.1	-59.8	-4.0
	2	979.8	12,377,930	848.9	130.9	13.4
	3	1,628.4	23,265,168	1,595.6	32.8	2.0
3rd experiment	1	2,004.9	30,177,256	2,168.1	-163.2	-8.2
	2	1,217.9	17,288,120	1,242.1	-24.2	-2.0
	3	1,510.5	22,118,519	1,589.1	-78.6	-5.2
	4	1,614.8	19,927,113	1,431.7	183.1	11.3

$$*Error(\%) = \frac{Measured\ fruit\ mass - Estimated\ fruit\ mass}{Measured\ fruit\ mass} \times 100$$

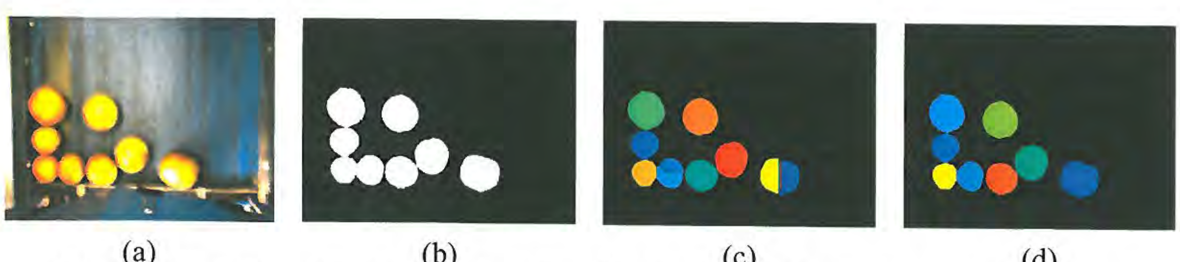


Fig. 3 - Fruit separation result with watershed transform: (a) original image, (b) segmented binary image, (c) after watershed transform without H-minima transform, and (d) after watershed transform with H-minima transform.

Table 3 - Potential fruit counting and diameter distribution.

	Set number	Number of fruit						Average (cm)
		5~6 cm	6~7 cm	7~8 cm	8~9 cm	9~10 cm	Sum	
2nd experiment	1	544	2016	2484	573	52	5669	7.0
	2	605	1419	1190	166	18	3398	6.7
	3	1059	3347	2131	216	44	6797	6.7
3rd experiment	1	994	3257	2660	515	64	7760	6.8
	2	680	2199	1377	192	24	4472	6.6
	3	962	3226	1637	119	15	5959	6.6
	4	1325	2943	1219	137	28	5652	6.4

Areas where progress exceeded expectations: The following three algorithms contributed to the performance of the system by increasing the fruit detection and size estimation.

- Image segmentation algorithm using logistic regression model to perform the detection of citrus fruit in an image.
- HSAR (highly saturated area recovering) algorithm to increase the segmentation accuracy.
- H-minima transform based watershed algorithm to separate neighboring fruit that is joined together in the binary output image.

Areas where progress didn't meet expectations: There was an issue of synchronization between the moving speed of conveyor belt of the cleaning machine and the speed of image acquisition, however the developed system yielded good results.

Impact of accomplishments towards overall goals of funding: This research was conducted as a preliminary step towards implementing an advanced citrus yield mapping system on the citrus debris cleaning machine. The developed system showed great potential to be used in a grove in real-time, which allows citrus growers to monitor fruit yield in the grove.

Presentations associated with 2011-12 efforts: A poster, titled "Machine vision based citrus mass estimation during post-harvesting using supervised learning algorithms", was presented at the International Symposium on Mechanical Harvesting & Handling Systems of Fruits & Nuts held in Lake Alfred, FL on April 3, 2012.

Publications from 2011-12 efforts:

Refereed:

J. S. Shin, W. S. Lee, R. Ehsani. 2012. Postharvest citrus mass and size estimation using logistic classification model and watershed algorithm. Biosystems Engineering (Under review).

Non-refereed:

J. S. Shin, W. S. Lee, R. Ehsani. 2012. Machine vision based citrus mass estimation during post-harvesting using supervised learning algorithms. International Symposium on Mechanical Harvesting & Handling Systems of Fruits and Nuts. April 2-4, 2012, Citrus Research and Education Center, University of Florida/IFAS, Lake Alfred, FL.

Next steps: During FY 2012-13, a machine vision system will be developed that can estimate the number of fruit drop on the ground. The proposed system will help other research projects in the Citrus Initiative.