

A RAPID PROTOTYPING DESIGN TOOL FOR PEAR HARVEST-AID PLATFORMS UTILIZING 3D FRUIT REACHABILITY AND KINEMATIC MODELING

Stavros Vougioukas¹, Rajkishan Arikapudi¹, David Slaughter¹, Fadi Fathallah¹, Rachel Elkins², Chuck Ingels³

¹Biological and Agricultural Engineering Department, University of California, Davis.

²University of California Cooperative Extension, Lake and Mendocino Counties.

³University of California Cooperative Extension, Sacramento County.

ABSTRACT

A design tool is being developed to evaluate the fruit picking efficiency and speed of pear harvesting or harvest-aiding mechanized system designs. Such a tool can enhance and accelerate the design of novel harvesting equipment. Picking efficiency and speed depend on the spatial distribution of fruits in the canopy, and on tree branch architecture. Registering fruit locations on trees has been a very time-consuming and expensive process. A novel sensing system was developed in 2012 that can record the locations of fruits on pear trees at a speed comparable to the fruit picking speed during commercial harvest. The system was tested in the summer of 2012 and fruit locations were computed for approximately 15,000 pears. In 2013 the system was developed further in order to improve its accuracy. In the summer of 2013 fruit locations were digitized for a large number (~ 15,000) Bartlett and Bosc pears on trees of the standard 'open-vase', trellis and high-density trellis training systems. Currently, work is under way to digitize the geometries of entire trees of the above-mentioned training systems. Also, software is being written to perform the harvesting simulation.

1. OBJECTIVES

The main objectives of this year's project were to: a) measure and record the positions of pear fruits in a large number of tree canopies along orchard rows; b) digitize entire pear trees of different training systems.

2. MEASUREMENT OF FRUIT LOCATIONS

A novel system was developed, which utilizes high-frequency ultra-wide band radio signals, and trilateration. More specifically, during manual harvesting, each fruit picker carried a mobile radio transmitter and receiver on his belt and wore gloves, with an antenna attached on each glove. The antennas of both hands were connected to a radio transmitting and receiving unit. A mobile trailer carried four radio receiver-transmitter units (beacons) and corresponding antennas; the distance of each beacon antenna from the antenna on each worker's hand was measured periodically. By combining the four distances of each antenna from the beacons, the three-dimensional coordinates of each glove were computed, with respect to the trailer. The trailer was

equipped with a high-precision GPS that measured the geographical position of the trailer with an accuracy of less than one inch, and an inclinometer, i.e., an attitude sensor that measured roll, pitch and heading trailer angles. Using the data from these two sensors, the geo-referenced coordinates of the worker gloves with respect to the world frame (UTM) were computed. Finally, every time a worker picked a fruit, the event was registered manually by pushing a button on a wireless controller; the glove position at that time instant gave us the approximate position of the grasped pear.

3. RESULTS

In the summer of 2013, fruit location data were gathered from the following sites:

DATE: 7/24/2013 WHAT: Pear trees, standard open-vase AGE: ~33 yrs TREE HEIGHT: ~14ft VARIETY: Bosc WHERE: Joe Green Ranch	DATE: 8/12/2013 WHAT: Pear trees, Trellis AGE: ~12 yrs TREE HEIGHT: ~16ft VARIETY: Bartlett WHERE: Dan Family Ranch, Lakeport
DATE: 8/13/2013 WHAT: Pear trees, standard open-vase AGE: ~15 yrs TREE HEIGHT: ~13.5ft VARIETY: Bartlett WHERE: Ruddick Ranch, Ukiah	DATE: 8/14/2013 WHAT: Pear trees, High Density Trellis AGE: ~ 3 yrs TREE HEIGHT: ~9ft VARIETY: Bartlett WHERE: Ruddick Ranch, Ukiah

3.1 Joe Green Ranch

Results from the field experiment at Joe Green Ranch (7/24/13) are given next. Data were collected from three trees along a row shown in Fig. 1.



Fig. 1 Data collected at Joe Green Ranch (7/24/13) from three pear trees is inside the yellow rectangle. A map of the fruit locations in 3D is shown in Fig. 2.

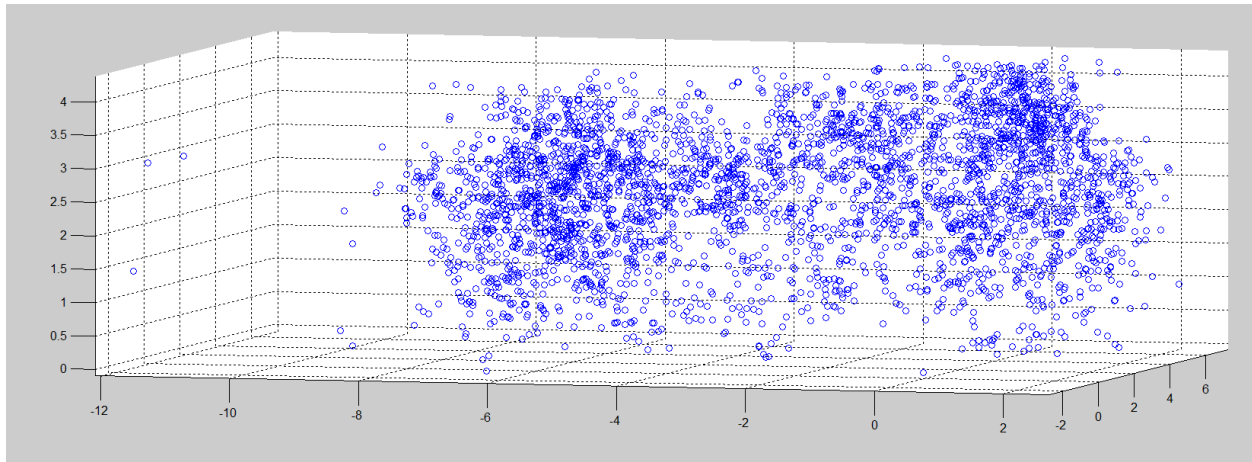


Fig. 2 Fruit locations in the canopies of three trees in a row (height in meters).

The yield of each tree can be seen in Fig. 3. The trees within a row vary in size and age which effects the fruit bearing capacity of individual trees.

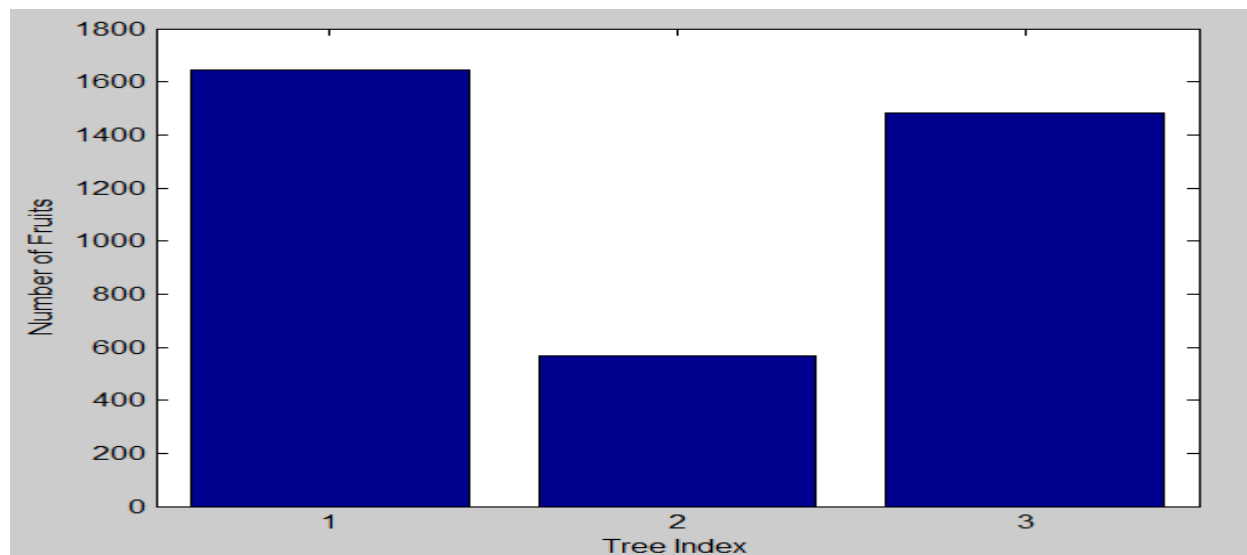


Fig. 3 Number of fruits (yield) per tree.

The height distribution of the pears in a row is very important for mechanization because it sets the specifications for the lifting system of any harvesting equipment. The normalized histogram for the three trees in the row is given in Fig. 4. The mean value of this height is $E(h) = 8.29$ ft, and the standard deviation, $\sigma = 3.11$ ft.

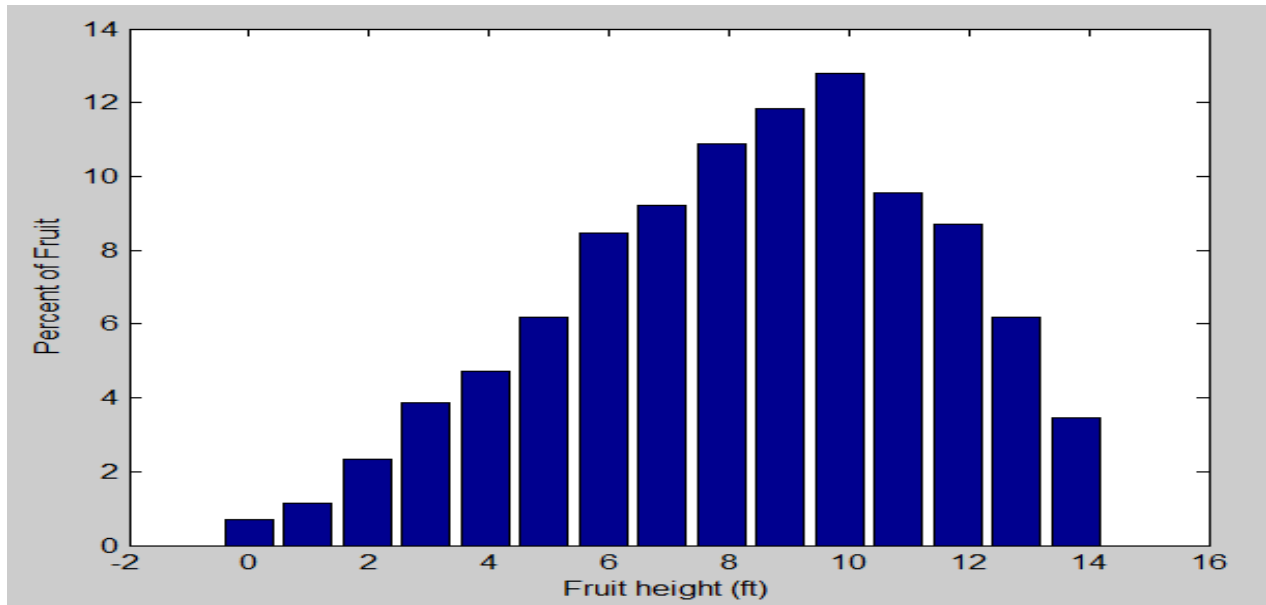


Fig. 4 Fruit height normalized histogram.

The corresponding cumulative height histogram is given in Fig. 5. It can be seen that these 33-year-old trees bear fruit from near the ground to their tops. In this orchard, about 70% of the fruit is above 6ft, i.e., the average picker on the ground cannot reach them.

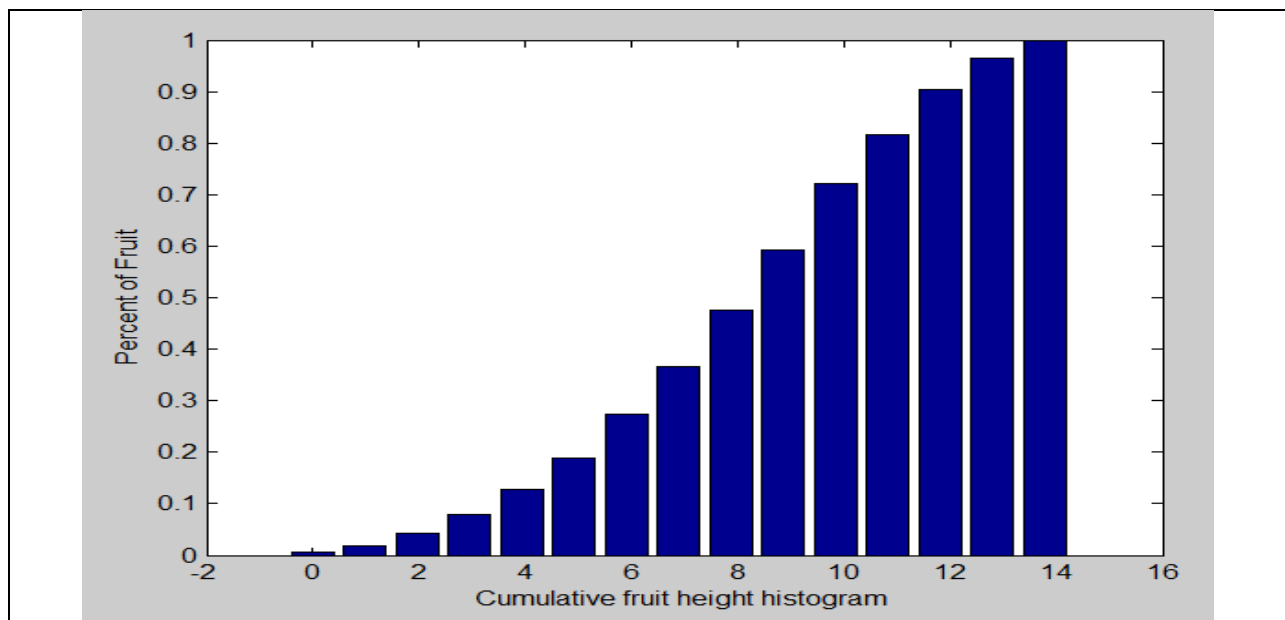


Fig. 5 Cumulative fruit height histogram.

Let us define for each fruit, its smallest distance, d , from the vertical planes in the middle of the rows to the right and left of the tree is defined. The normalized histogram of this distance is an approximation of the probability density function, i.e., the probability that a fruit is at a certain distance from the row centers. The standard deviation, σ , of this distribution can be used as a *metric* that expresses the uniformity of

fruit reachability from a worker or machine moving along a row. The normalized histogram of this distance is shown in Fig. 6. This is an approximation to the probability density function of the distance variable. The mean value of this distance is $E(d) = 9.06$ ft, and the standard deviation, $\sigma = 2.24$ ft.

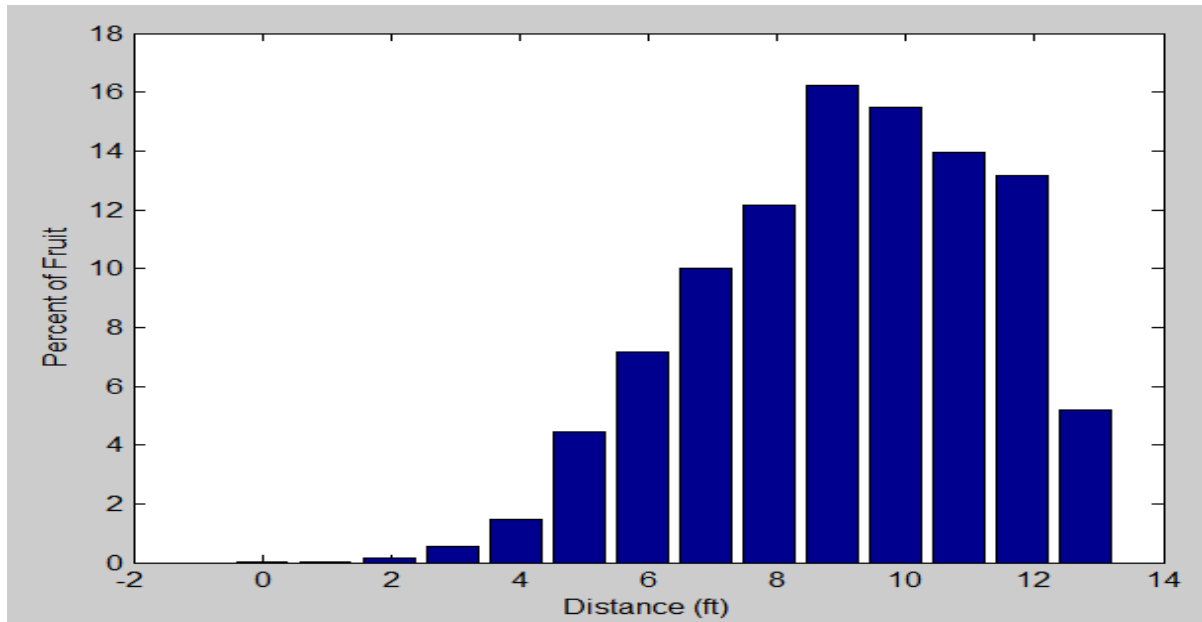


Fig. 6 Normalized histogram of fruit horizontal minimum distance from the left and right row centers.

The closer to zero the standard deviation is, the easier it is to reach fruit from the row without moving towards the tree or in the space between trees. Trees trained in hedgerows are expected to have a smaller standard deviation than standard open-vase trees.

3.2 Dan Family Ranch

Results from the field experiment at Dan Family Ranch (8/12/13) are given next. Data were collected from seven trees along a row shown in Fig. 7.



Fig. 7 Data collected at Dan Family Ranch (8/12/13) from seven pear trees inside the yellow rectangle.

A map of the fruit locations in 3D is shown in Fig. 8.

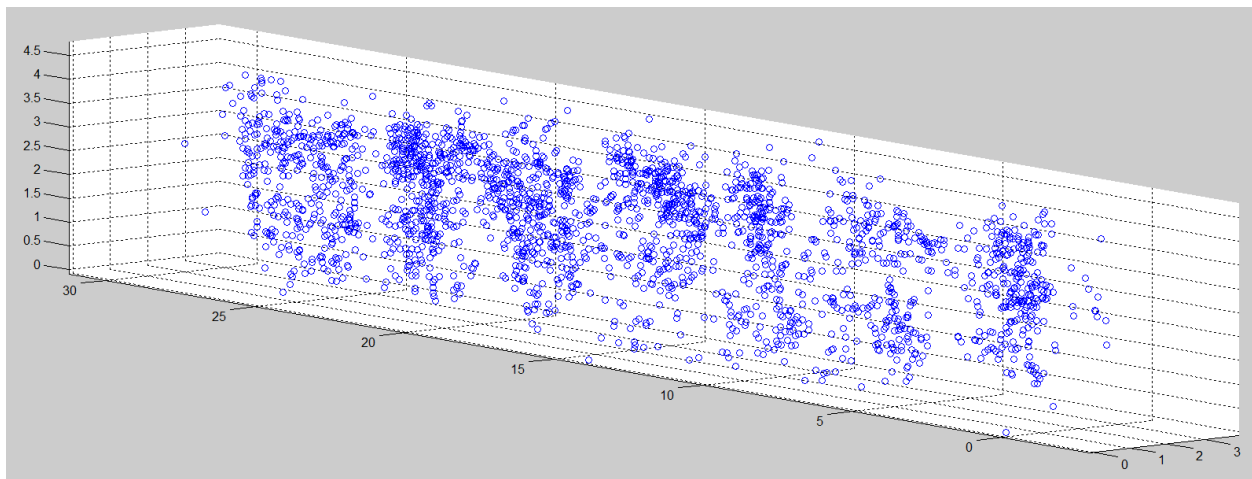


Fig. 8 Fruit locations in the canopies of seven trees in a row.

The yield of each tree can be seen in Fig. 9.

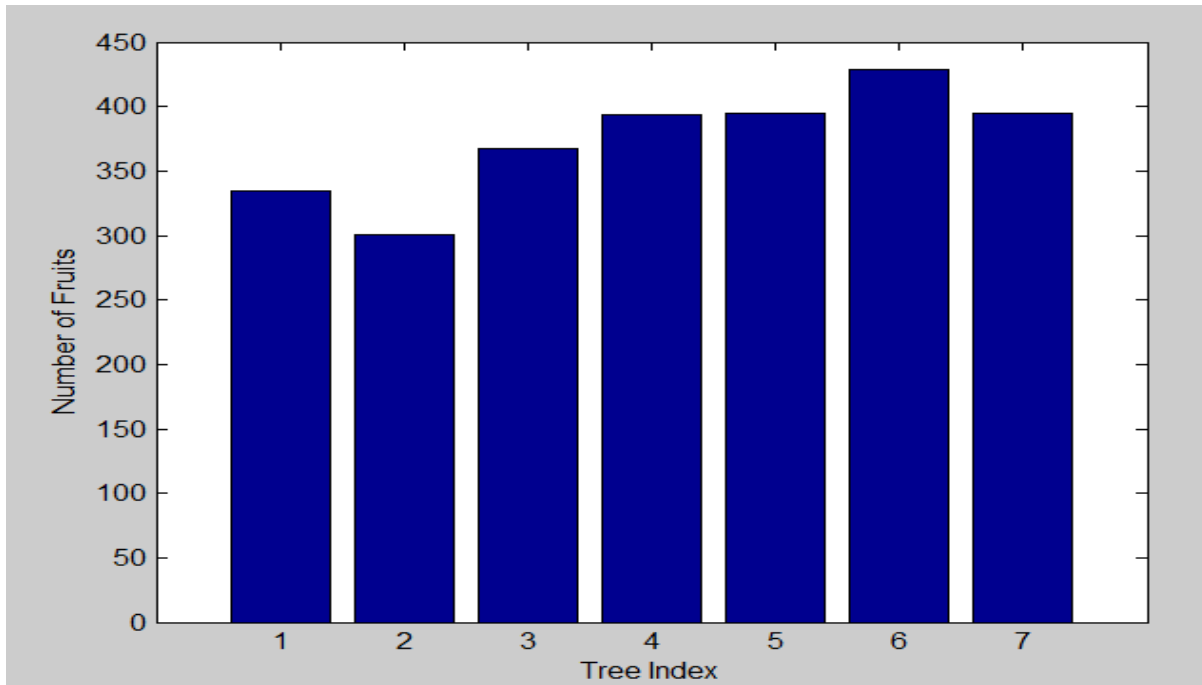


Fig. 9 Number of fruits (yield) per tree.

The height distribution of the pears for the seven trees in the row is shown in the normalized histogram in Fig. 10. The mean value of this height is $E(h) = 8.6$ ft, and the standard deviation, $\sigma = 3.4$ ft.

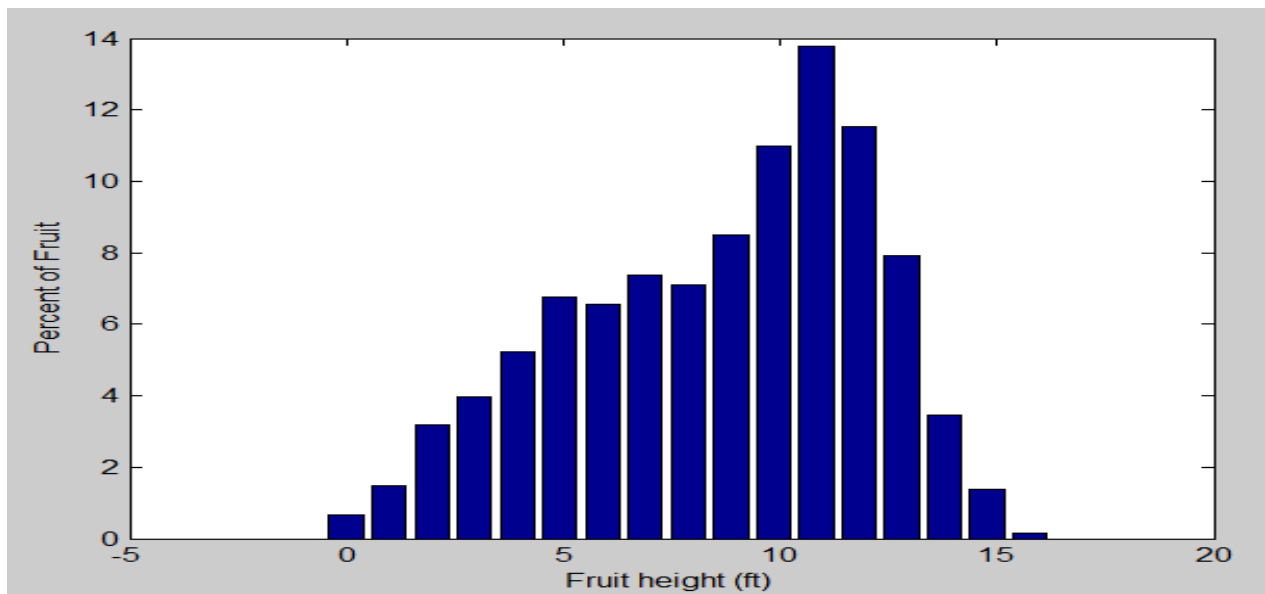


Fig. 10 Fruit height normalized histogram.

The corresponding cumulative height histogram is given in Fig. 11. It can be seen that these old trees bear fruit from near the ground to their tops; 70% of the fruit is above 6ft.

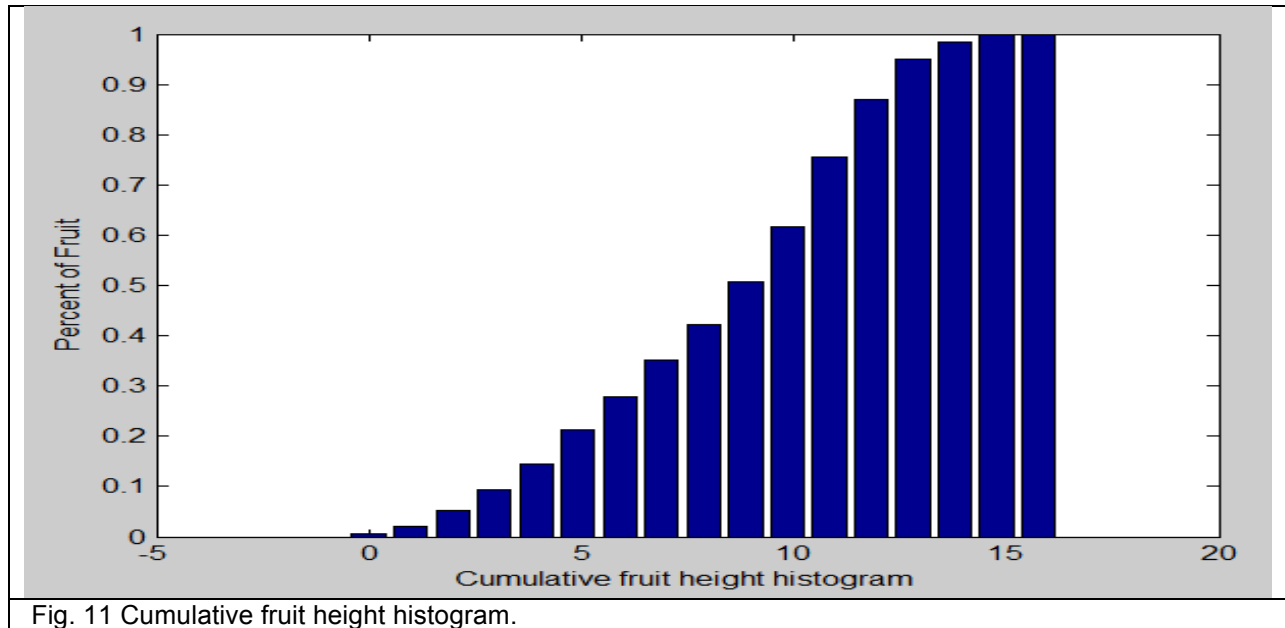


Fig. 11 Cumulative fruit height histogram.

The normalized histogram of the fruit distances from the row-centers is shown in Fig. 12. The mean value of minimum distance of the fruits from the row center is $E(d) = 3.96$ ft, and the standard deviation, $\sigma = 1.4$ ft. This standard deviation is smaller than the one measured at Joe Green ranch; in fact, based on visual inspection it can be said that the tree canopies at this part of the orchard were pruned well compared to other parts of the same ranch or in the other orchards we visited.

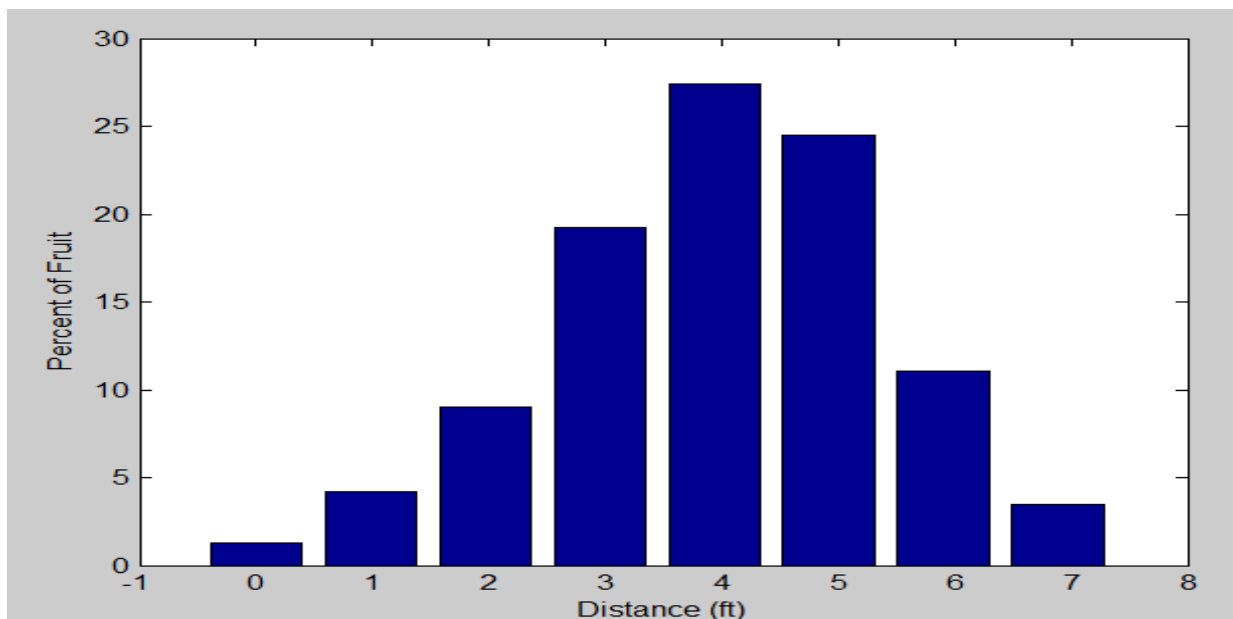


Fig. 12 Normalized histogram of fruit horizontal minimum distance from the left and right row centers.

3.3 Ruddick Ranch

Results from the field experiment at Ruddick Ranch (8/13/13) are given next. Data were collected from four trees along a row shown in Fig. 13.



Fig. 13 Data collected at Ruddick Ranch (8/13/13) from four pear trees inside the yellow rectangle.

A map of the fruit locations in 3D is shown in Fig. 14.

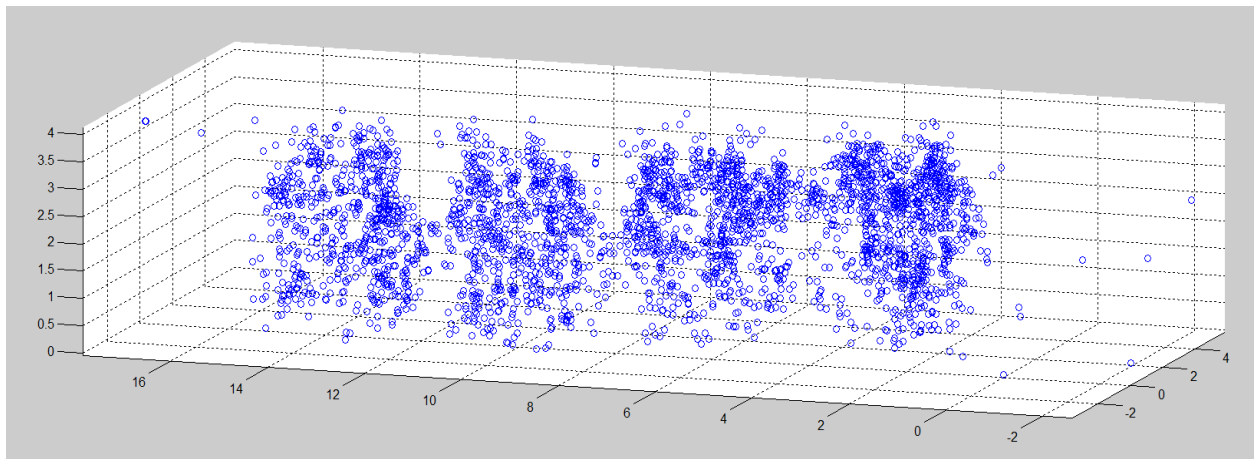


Fig. 14 Fruit locations in the canopies of four trees in a row.

The yield of each tree can be seen in Fig. 15.

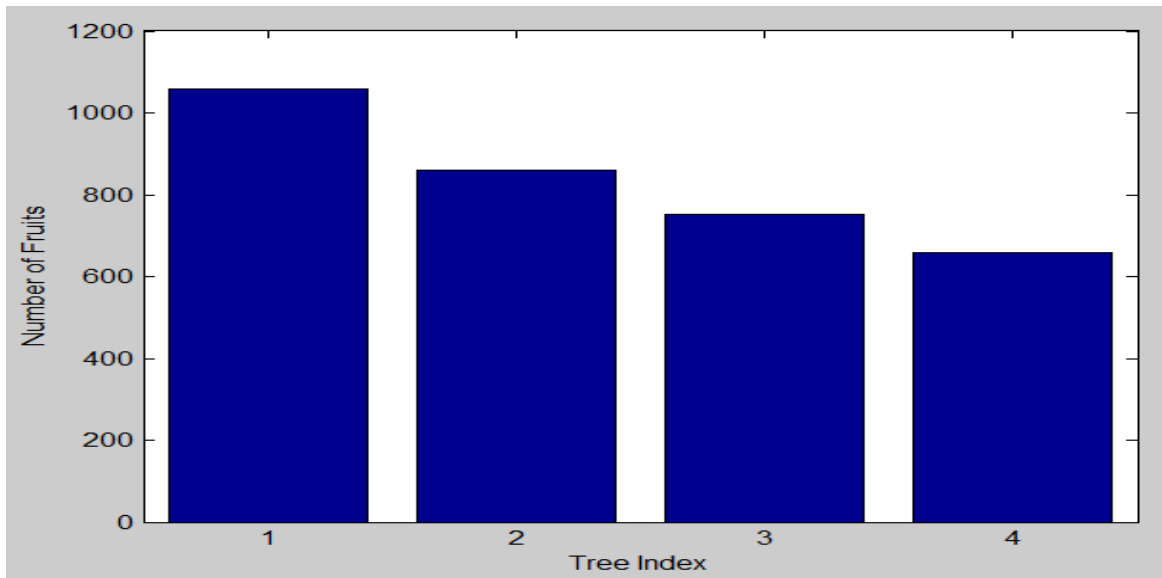


Fig. 15 Number of fruits (yield) per tree.

The normalized histogram for the four trees in the row is given in Fig. 16. The mean value of this height is $E(h) = 6.98$ ft, and the standard deviation, $\sigma = 2.99$ ft.

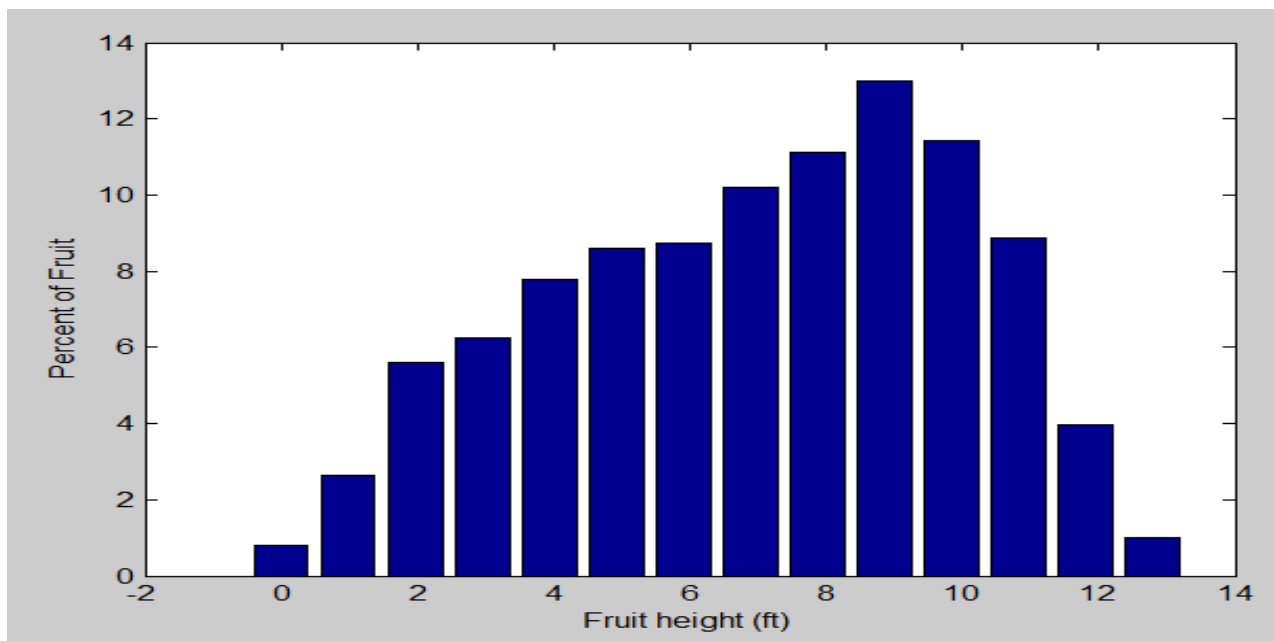


Fig. 16 Fruit height normalized histogram.

The corresponding cumulative height histogram is given in Fig. 17. It can be seen that these 15-year-old trees bear fruit from near the ground to their tops. In this orchard, about 60% of the fruit is above 6ft.

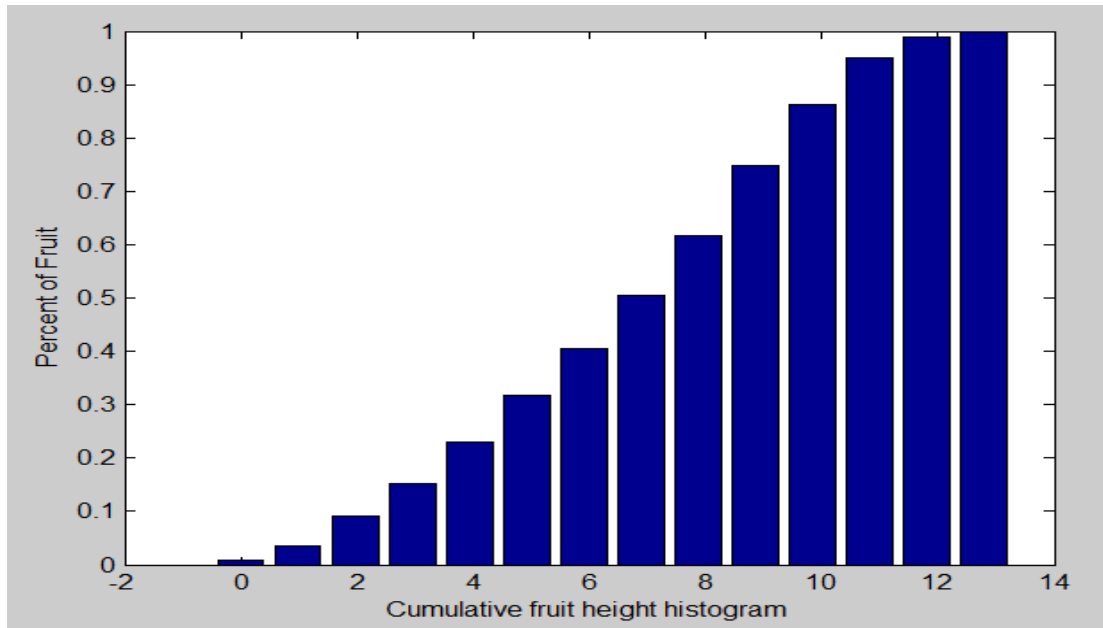


Fig. 17 Cumulative fruit height histogram.

The normalized histogram of the fruit distances from the row centerline is shown in Fig. 18. This is an approximation to the probability density function of the distance variable. The mean value of this distance is $E(d) = 8.04$ ft, and the standard deviation, $\sigma = 1.96$ ft.

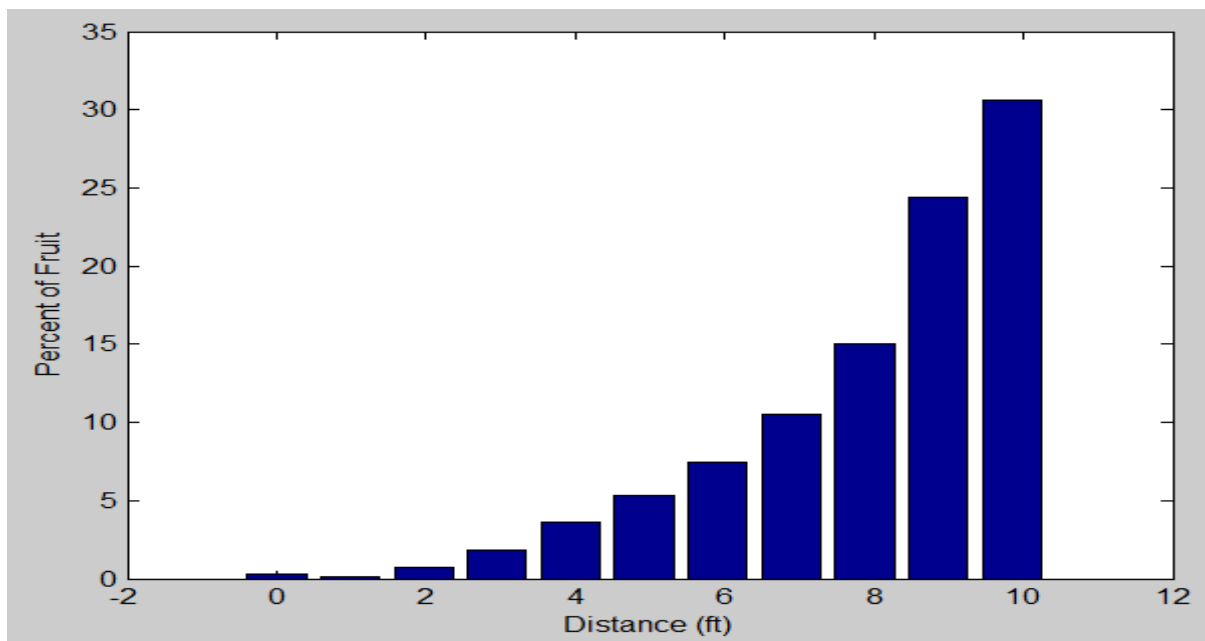


Fig. 18 Normalized histogram of fruit horizontal minimum distance from the left and right row centers.

3.4 Ruddick Ranch

Results from the field experiment at Ruddick Ranch (8/14/13) are given next. Data were collected from twenty-eight trees along a row shown in Fig. 19.



Fig. 19 Data collected at Ruddick Ranch (8/14/13) from twenty-eight pear trees inside the yellow rectangle

A map of the fruit locations in 3D is shown in Fig. 20.

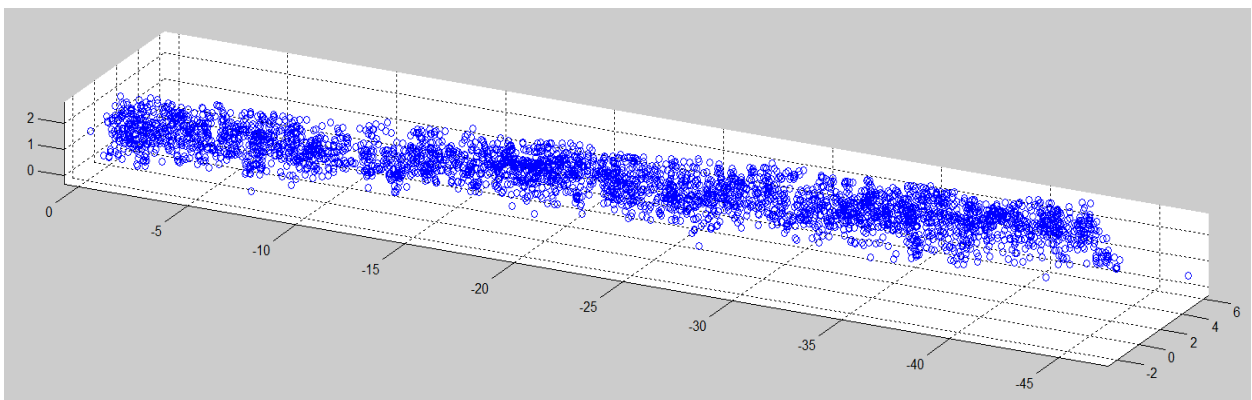


Fig. 20 Fruit locations in the canopies of twenty eight trees in a row.

The yield of each tree can be seen in Fig. 21.

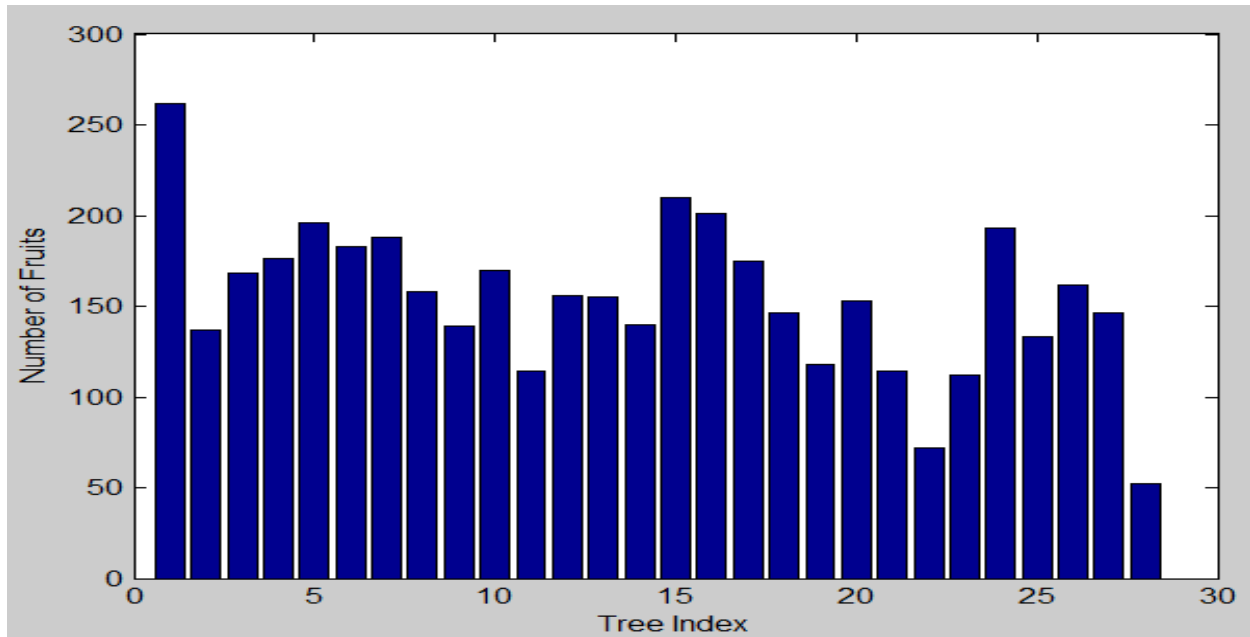


Fig. 21 Number of fruits (yield) per tree.

The height distribution of the pears for the twenty-eight trees in the row is shown in the normalized histogram in Fig. 22. The mean value of this height is $E(h) = 5.50$ ft, and the standard deviation, $\sigma = 1.98$ ft.

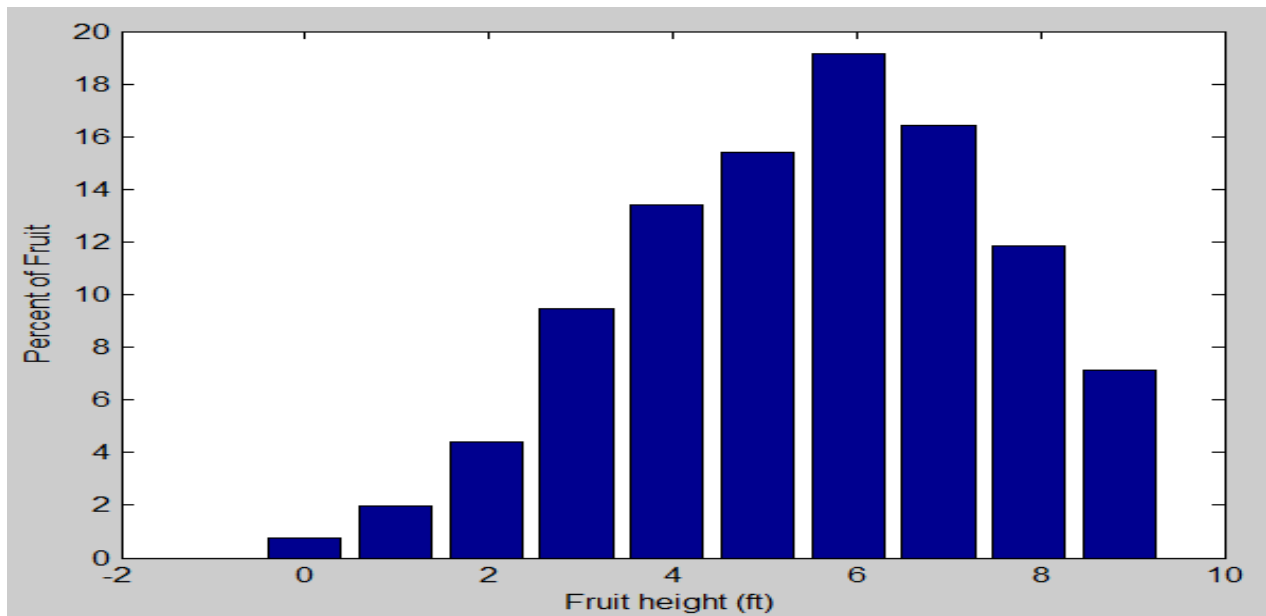


Fig. 22 Fruit height normalized histogram.

The corresponding cumulative height histogram is given in Fig. 22. It can be seen that these 3-year-old trees bear fruit from near the ground to their tops; 35% of the fruit is above 6ft.

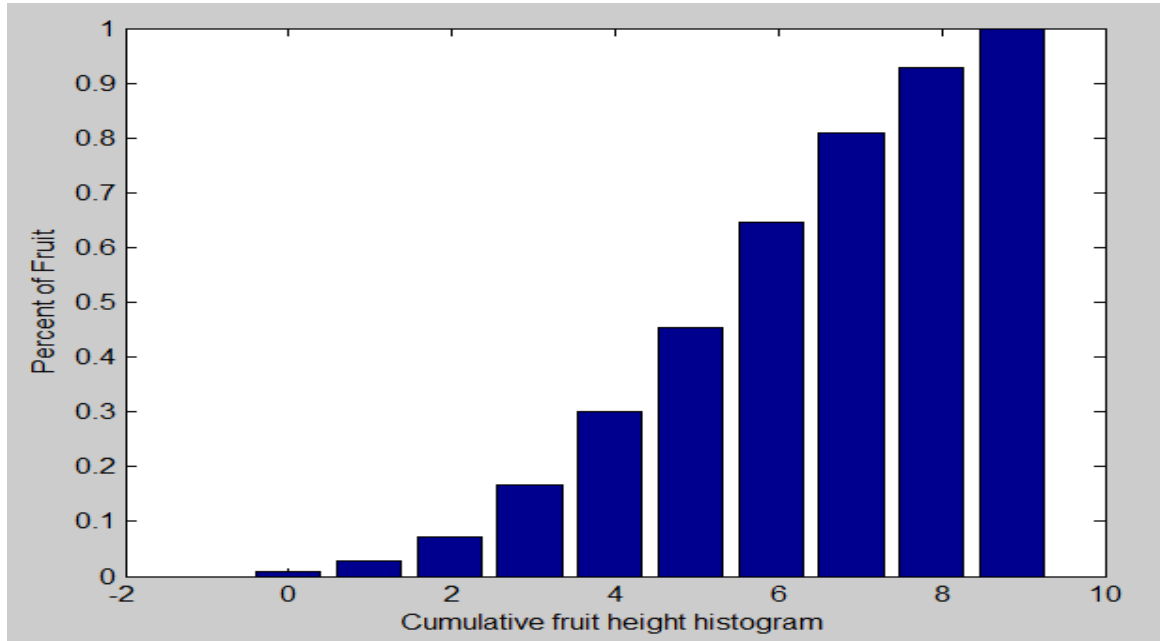


Fig. 23 Cumulative fruit height histogram.

The normalized histogram of the fruit distances from the row-centers is shown in Fig. 24. The mean value of this distance is $E(d) = 3.74$ ft, and the standard deviation, $\sigma = 1.0$ ft. The pair of distance and standard deviation is much smaller in the high-density trellis than in all other systems digitized. This is a desirable feature for mechanical harvesting systems.

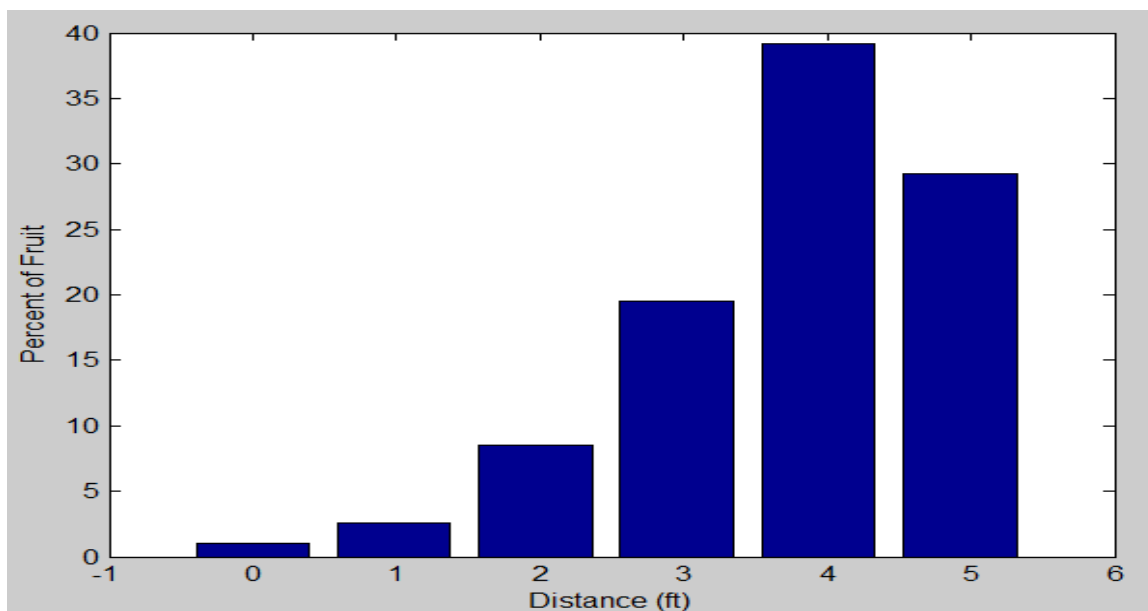


Fig. 24 Normalized histogram of fruit horizontal minimum distance from the left and right row centers.

4. Current Work – Tree Digitization

Current work focuses on the digitization of pear trees, so that their geometries can be used to evaluate machine or picker harvesting speeds in the design tool under development. Trees of open-vase, trellis and high-density trellis architectures will be digitized.

4.1. Materials and Methods

To test the design of any tree harvesting or harvest-aiding mechanized system we should take into account the spatial distribution of fruits in the canopy and the tree geometry. To collect the data points on the surface of the tree we use the digitization approach. The equipment we are using is the Polhemus PowerTRAK 360™ digitizer, with a G⁴ RF module, a *Hub* and a *Source* as shown in Fig.32.

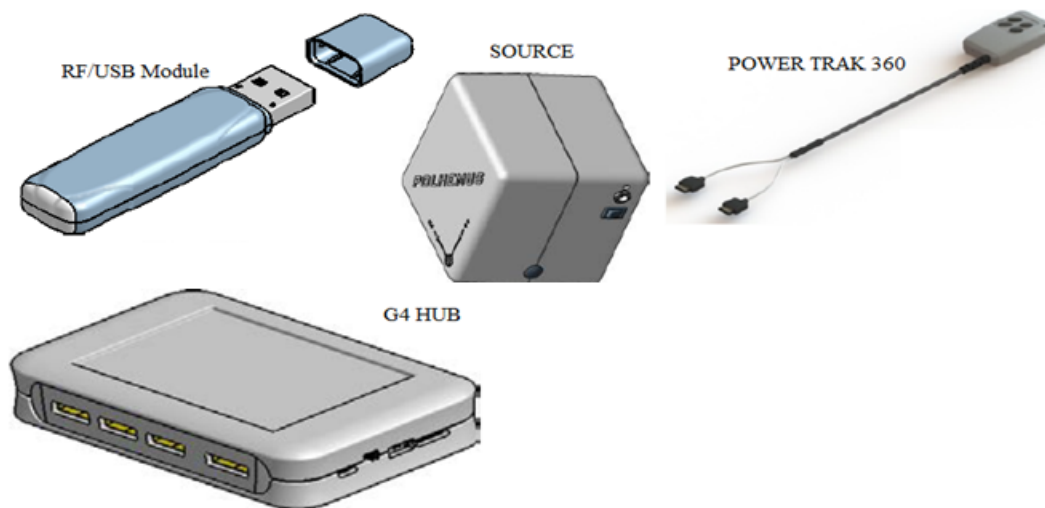


Fig. 25: G⁴ system overview

4.1.1. Operation

The device called 'Source' produces magnetic dipole fields, e.g. fields created by closed loops of electric current. The 'Sensor' has an electromagnetic receiver to track its position by detecting the fields that are on the three axes of the source. Due to the symmetry of the magnetic fields the sensor computes two possible positions that are equal and opposite of each other. To determine the actual position of the sensor, the startup hemisphere is to be specified at the start of tracking.

A special enclosure and a stylus were designed and constructed at UC Davis to accommodate precise positioning and measurement of points on the surface of trees. The modified sensor is shown in Fig. 26.



Fig. 26 Digitization sensor Powertrak 360 with enclosure and stylus.

4.1.2. Accuracy, Range and Precision

The static accuracy of the device for different ranges is given by the company and is shown in the Table 1.

Table1: Accuracy Measurements

Static Accuracy		
Range	Orientation	Position
1 meter/3.3 ft	0.50 degrees RMS	0.08 inches/0.2 cm RMS
2 meter/6.5 ft	0.75 degrees RMS	0.25 inches/0.64 cm RMS
3 meter/9.8 ft	1.00 degrees RMS	0.50 inches/1.27 cm RMS

The precision of the device is calculated via experimentation and estimated that the sensor has a precision of better than 1cm when the tracking volume is about 5ft x 5ft x 5ft from the source. The setup of the experiment is described as follows. The source is placed at 0ft x 0ft and the sensor mounted on a cardboard is moved along the rectangular grid having dimensions 10ft x 8ft at different heights. 1000 readings were recorded at each position as shown in the Fig. 27 and the error is calculated using the Euclidian distance formulae.

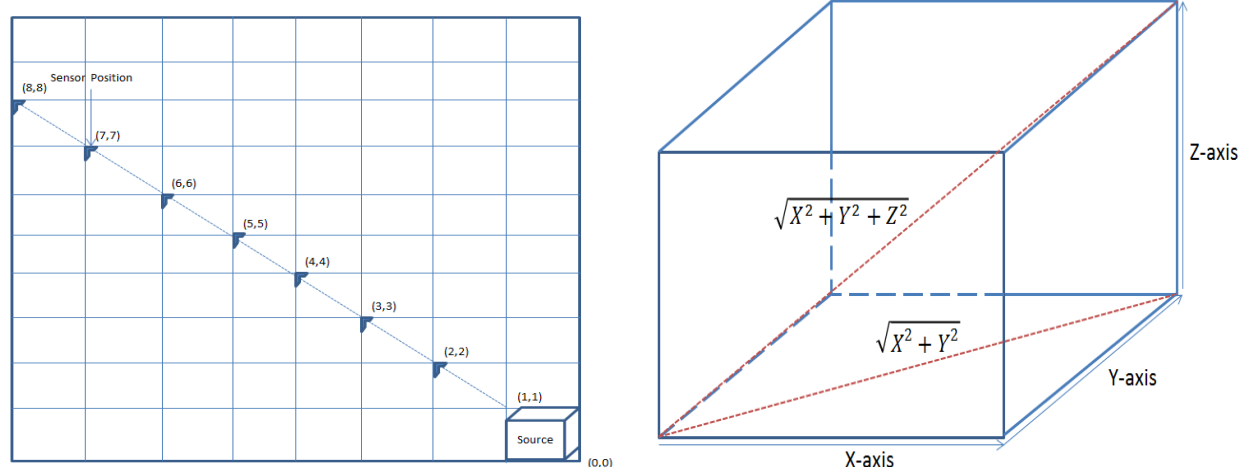


Fig. 27: Position of Sensor with respect to G^4 source and Euclidian Distance for a cube

To better estimate the error pattern, the volume of the cube is scaled to an equivalent Euclidian distance as shown in Fig. 27. The error readings for the experiments conducted were shown in Table 2.

Table 2: Precision Measurements

Sensor Position	Error values in centimeters for the sensor position (X, Y, Z)			
Position (ft) (X, Y)	H0 Ground (Z)	H1 1.54 ft (Z)	H2 0.83 ft (Z)	H3 2.15 ft (Z)
1,1	0.0114 cm	0.1131 cm	0.0223 cm	0.0314 cm
2,2	0.012 cm	0.1337 cm	0.0715 cm	0.0571 cm
3,3	0.1022 cm	0.1555 cm	0.0463 cm	0.1475 cm
4,4	0.1057 cm	0.1045 cm	0.1736 cm	0.1544 cm
5,5	0.4326 cm	0.4558 cm	0.6551 cm	0.3489 cm
6,6	0.7796 cm	1.051 cm	0.9606 cm	0.6554 cm
7,7	1.7268 cm	1.4164 cm	2.0479 cm	1.4115 cm
8,8	2.8553 cm	3.1245 cm	3.7265 cm	2.4587 cm

From the table it is clear that the maximum Euclidian distance that is possible for the error magnitude to be better than 1cm is 8.75 ft. Converting this to volume we found that the volume of the cube to be 5ft x 5ft x 5ft which equivalents to 8.66 ft in distance.

From our experiments we conducted for recording the fruit locations in the tree canopy we found that the maximum volume of an individual tree is 10ft x 15ft x 15ft. To precisely digitize the trees whose maximum volume is 10ft x 15ft x 15ft we need 18 sources. As each source is confined to a coverage volume of 5ft x 5ft x 5ft these sources should be placed at appropriate locations to cover the entire volume of an individual tree. To achieve this we built a frame for the digitization process so that the sources were moved within the frame in sequence to cover the whole tree volume. We bought 6 sources to speed up the digitization process using which we increased the motion tracking volume to 5ft x 10ft x 15ft at any given instant. Since the sensor used for data collection is based on the interaction of magnetic fields created by the G^4 source and the field created by the Power Track 360TM the workspace should be free of metal to ensure the tracked volume has no interference. So, the frame that was built was made of wood to mitigate the error in the collected data.

4.2. Experimental Setup and Procedure

The geometry of the frame and the total volume of the tree to be covered are shown in Fig. 34. The positions of sources are indicated with numbers.

To cover the whole tree volume of 10ft x 15ft x 15ft we divided the workspace into two halves. Each half covers 5ft x 15ft x 15ft of volume. The setup of the frame on one side of the tree covers the first half and the second side will cover the second half of the tree. The setup of the frame in the desired workspace is shown in Fig. 28.

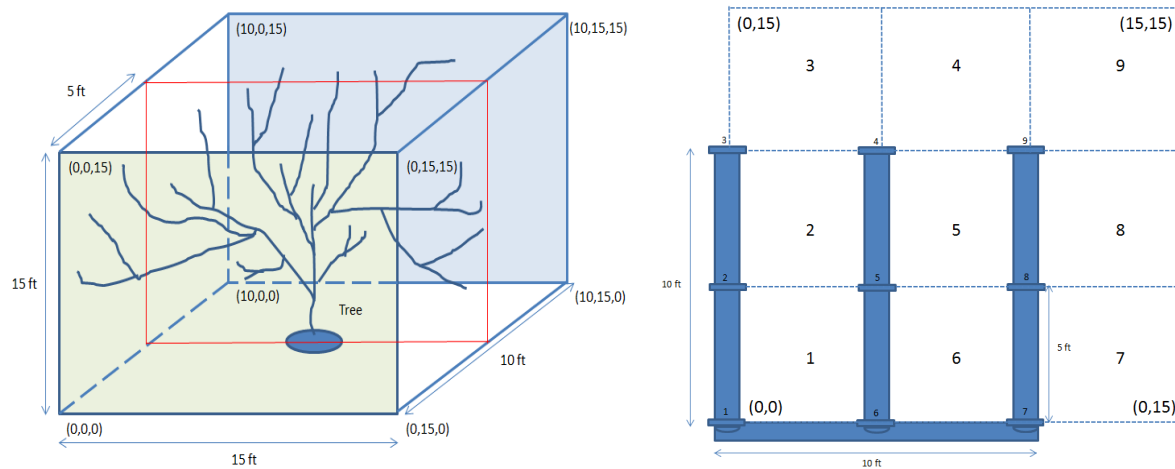


Fig. 28: Tree volume and the frame

The sources placed at 9 different locations as shown in Fig. 29 covers the desired volume on one side of the tree. The Y and Z axis are shown in Fig. 34. The X-axis covers in total a length of 10ft of which 5ft is being covered by the frame in the plane Y-Z.

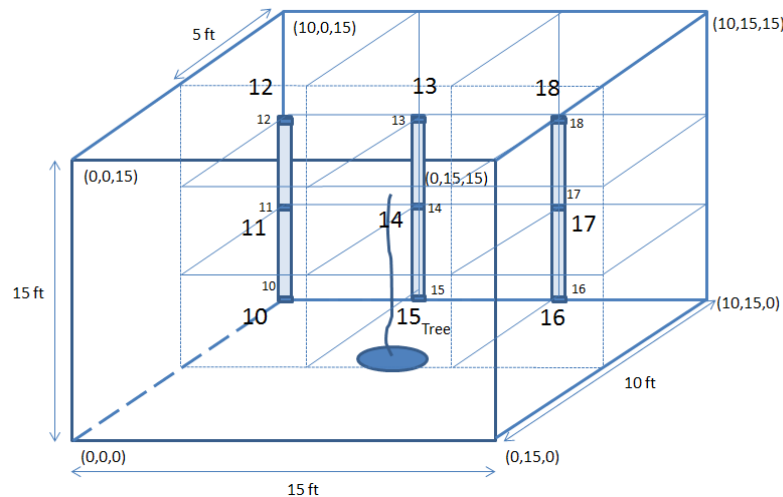


Fig. 29: Source Locations on the frame

The 6 sources were placed initially at points 1 through 6 which cover the volume of 5ft x 10ft x 15ft as shown in the Fig. 30. Once the digitization process is completed in the

volume of 5ft x 5ft x 15ft i.e. the volumes 1, 2 and 3 are covered then three of the sources from points 1, 2 and 3 are moved to locations 7, 8 and 9 as shown in the Fig. 36. The volumes 7, 8 and 9 are thus covered by the setup of the sources at their corresponding 7, 8 and 9 locations. This procedure results in the coverage volume on one side of the tree i.e. the volume of 5ft x 15ft x 15ft is covered. To cover the remaining volume of 5ft x 15ft x 15ft the same procedure is repeated on the second side of the tree.

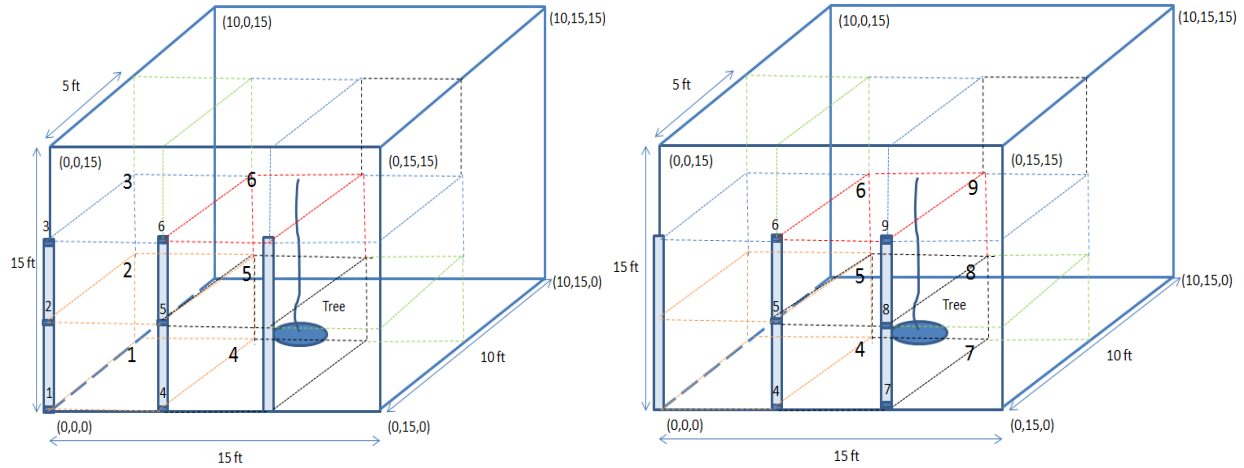


Fig. 30: Source Locations on the frame

4.3. Preliminary Test Results

A tree on campus is digitized which is shown in the Fig. 31. The trunk and two of its branches that were highlighted as shown were digitized and the results were given in the Fig. 31.

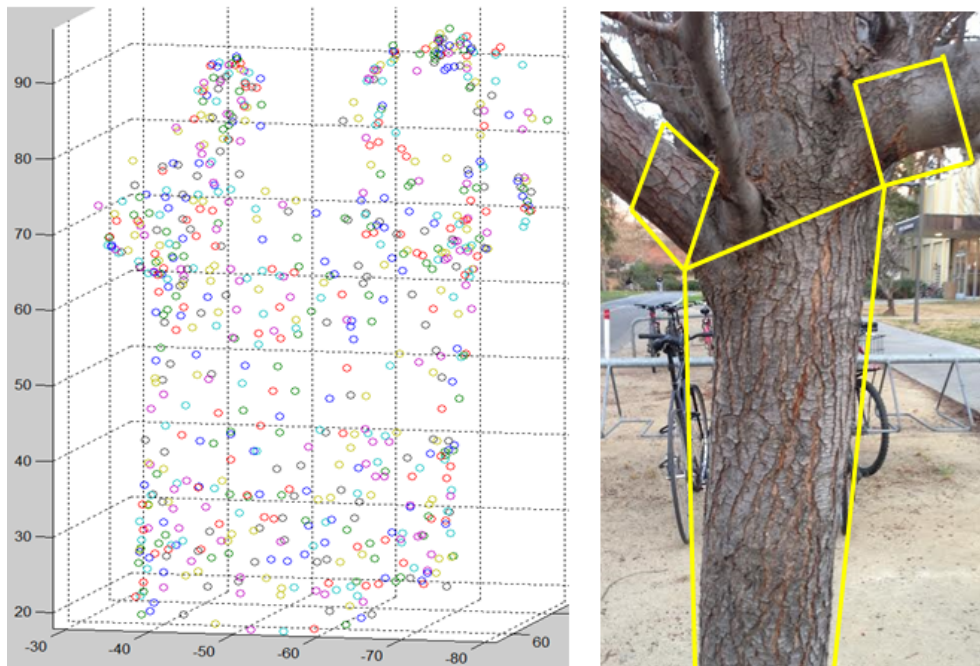


Fig. 31: Tree Digitization

5. DISCUSSION

The performance of the range measurement system was satisfactory and the accuracy achieved varied from 1" to 8", depending on the amount of foliage and line-of-sight conditions. However, in some instances the pickers would either pick fruit too quickly, or their bodies or the metallic ladders would interfere with the signal propagation path; this resulted in outliers in the data, i.e., ranges that were obviously erroneous or precision that was unacceptable ($> 4''$). These outliers were removed during the post-processing phase and the corresponding fruit positions were not included in the results. The software tools written for the year 2013 helped us in detecting those outliers during data collection so the percentage of outliers was significantly reduced. Overall, fruit positions for more than 15,000 fruits were collected; such a large dataset has never been available in the past. The collected data will be used as input to rapid-prototyping software that will be developed to assist in the design and evaluation of orchard automation machinery.

ACKNOWLEDGEMENTS

We would also like to thank Chris Frieders of Joe Green Ranch, Dan of Dan Family Ranch, and Chris Ruddick of Ruddick Ranch for letting us gather data during their harvesting season. Finally, the contributions of students, Garen Lewis, Fransisco Jimenez Jimenez and Farangis Khosro Anjom during the experiments are greatly appreciated.