DESIGN, ERROR CHARACTERIZATION AND TESTING OF A SYSTEM TO MEASURE LOCATIONS OF FRUITS IN TREE CANOPIES

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ABSTRACT

This paper presents the design, error characterization and testing of a mobile system which utilizes radio waves and trilateration to measure the locations of fruits inside tree canopies. The system achieves accuracy better than 20 cm, 95% of the time (mean error is 11 cm) within a large digitizing volume of 15 m^3, and a fruit position digitization rate of approximately 1 fruit per second. The system was tested successfully in commercial orchards; its high digitizing rate makes it practical to map the variability of fruit properties within tree canopies, for large numbers of trees.

Keywords: Precision agriculture, fruit localization, fruit maps.

INTRODUCTION

Mapping the variability of fruit size and quality within tree canopies in commercial orchards is an important tool for implementing precision horticulture. To do so at a reasonably fast rate requires localization technologies that offer sufficient speed and accuracy, at a range long enough to cover entire trees – or sets of trees.

The first reported effort to measure fruit locations on trees was by Schertz and Brown (1966), who measured the coordinates of citrus fruits by lowering a plumb bob and recording its point of intersection with a board at ground level. Depending on yield and tree size, this approach required one-to-two days to map all the fruits on a single tree. Smith et al., (1992) used a theodolite to record the coordinates of kiwi fruits on vines. The accuracy was reported to be within millimeters of the position of each fruit. This method required unobstructed line-of-sight between each fruit and the theodolite. Each fruit required approximately 60 s, resulting in an effective rate of one vine per one-to-two days, depending on yields and vine size. Smith and Curtis (1996) used a three-dimensional position magnetic tracking system to digitize tree structure and measure fruit locations. The RMS static accuracy of the system was approximately 1 mm, within 1 m from the transmitter. The system's operational radius was limited to approximately 1.5 m; digitizing large trees was achieved by re-locating the transmitter to various positions. This system required 10-12 hours to digitize approximately 1500 points on a kiwi vine. Edan et al., (1991) measured fruit locations on twenty orange trees using a robotic manipulator on a mobile platform as digitizer. The arm tip was placed to contact each fruit and the location was calculated via the robot's forward kinematics. Accuracy and data collection speed were not reported; relocating the robot tip and moving the platform to reach each new fruit position should have required non-trivial effort, resulting in low collection rates.

This paper presents the design, error characterization and testing of a mobile system, which utilizes radio waves and trilateration to measure the locations of fruits inside tree canopies at rates that are high enough to be practical.

MATERIALS AND METHODS

In this work high-frequency radio signals were used to measure the locations of fruits in tree canopies. In particular, a fruit picker wore gloves with an antenna attached on each glove and a mobile trailer carried four radio beacons that periodically measured and logged their distances from the antenna on each worker glove. In practice, each distance measurement was actually the median value of five consecutive readings; hence, noisy outliers were removed. Every time a worker grasped a fruit (to pick it), the time instant of this event was registered manually by pushing a button on a wireless controller. Data from an RTK-GPS and an inclinometer on the trailer made it possible to compute beacon coordinates with respect to a fixed world frame (georeferenced). By combining the four distances of a glove antenna from the trailer radio beacons at that time instant, the georeferenced coordinates of the glove were computed; these coordinates approximated the fruit position.

The radio signals were transmitted and received using the PulsON 400 Ranging and Communications Modules (P400 RCM) from Time Domain, Inc., Huntsville, AL, USA. The P400 RCM is an Ultra Wideband (UWB) radio transceiver that accurately and reliably measures the distance between two P400 RCM omnidirectional antennas (Fig. 1). The units operate in the band of 3.1GHz to 5.3 GHz with a center frequency at 4.3 GHz, a maximum range of 125 m, and a measurement period of 20ms.

The Trimble AgGPS 542 GNSS/RTK GPS System was used to collect real-time, high-accuracy geo-referenced trailer location data. The Ag542 Rover GPS received corrections from an Ag 542 Mobile Base Station GPS using 900Mhz radio-modems integrated in the receivers. Also, a wireless attitude and heading sensor by YEI Technology, Inc. (Portsmouth, OH, USA) was used to measure the trailer's roll, pitch and heading angles. The sensor features a 2.4GHz DSSS communication interface and a rechargeable lithium-polymer battery. It uses triaxial gyroscope and accelerometer, and a compass sensor in conjunction with on-board Kalman filtering to determine orientation relative to an absolute reference in real-time. It has $\pm 1^{o}$ orientation accuracy for dynamic conditions, and repeatability $< 0.008^{o}$. The sensor outputs filtered absolute orientation angles in Euler format (pitch/roll/yaw).

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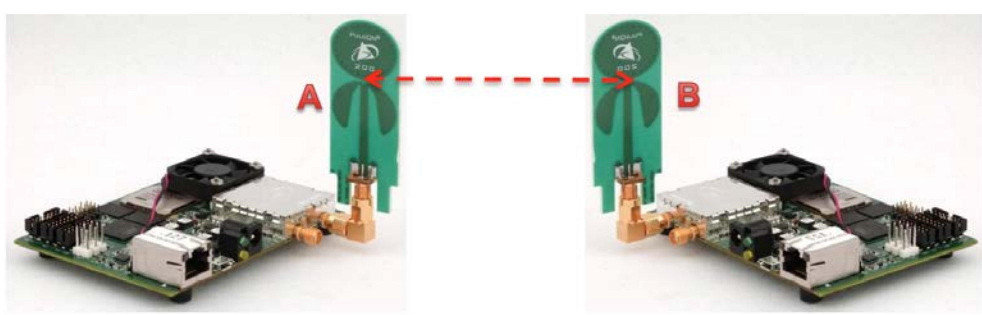


Fig. 1. Distance (red dotted line) is reported between antenna points A and B.

Error analysis

Each time a fruit is grasped by a worker the position coordinates of the fruit are approximated by the coordinates (x^*, y^*, z^*) of the antenna on the hand of the picker grasping the fruit; these coordinates are estimated via *trilateration*. The trilateration procedure uses the four measured distances $\hat{r}_i$ between each trailer beacon antenna and the glove antenna, in order to estimate the coordinates of the glove antenna. Let (x, y, z) be the true coordinates of the glove antenna with respect to the world frame, and r_i be the true (geometrical) distances between the ith beacon antenna on the trailer and the glove antenna:

$$r_i = \left((x - bx_i)^2 + (y - by_i)^2 + (z - bz_i)^2\right)^{1/2} \tag{1}$$

In reality, given that there is always some error ε_i in each range measurement, only the measured distance $\hat{r}_i$ is available, and the following equation is true:

$$\hat{r}_i = r_i + \varepsilon_i \tag{2}$$

The trilateration procedure estimates the coordinates of the glove antenna ${}^{WF}\mathbf{p} = [x^* \; \mathrm{y}^* \; \mathrm{z}^* \; 1]^T$ (expressed in the world frame) by computing a nonlinear minimization of the total squared error between measured and true distances:

$$(x^*, y^*, z^*) = \underset{x,y,z}{\arg\min} \sum_{i=1}^{4} \left(\hat{r}_i^2 - \left((x - bx_i)^2 + (y - by_i)^2 + (z - bz_i)^2\right)\right) \tag{3}$$

All calculations are performed using Matlab R2013a (Math Works, Natick, MA, USA) and equation (3) is solved using the *fminsearch()* Matlab optimization function.

In order to assess the statistics of the trilateration error, we need to know the statistics of the range measurement error ε_i, and also study how this error propagates through the nonlinear processing of the noisy range measurements in Eq. (3) (Papoulis and S.Unnikrishna, 2001).

Range error estimation

Let r be the true distance between two RCM antennas measured using a laser, and $\hat{r}$ be the distance reported by the RCMs. The reading contains an error ε, i.e., $\hat{r} = r + \varepsilon$. According to the manufacturer, in a static scenario (units not moving) with a clear Line of Sight (LOS), the accuracy and precision (standard deviation) specifications for the RCM range measurements are 2.1 cm and 2.3 cm respectively. In our case, the glove antennas were located on the periphery of and inside tree canopies; therefore the range error statistics had to be estimated experimentally. In order to evaluate the error during the measurement with the RCMs, two experiments were planned; the first was performed in open space and the second in an orchard. In open space the error depends on the relative positioning and orientation between the antennas of the RCMs because the antennas are not perfectly omni-directional. Inside tree canopies the foliage is expected to contribute to this error, although not excessively, because the particular radio devices calculate the range using only the direct-path electromagnetic wave; scattered and reflected waves are neglected to a large extent. The statistics of the distance measurement error ε are evaluated by placing two RCMs at different heights, angles and distances closely matching those during actual data collection.

Consider two RCM beacons with co-ordinates ${}^{WF}\mathbf{b}_i = [bx_i \ by_i \ bz_i \ 1]^T$ where i=1, 2; one of the beacons acts as a transmitter (Tx) and the other as a receiver (Rx). Device calibration was performed (according to product manual) at a range of 3 m, with Rx and Tx antennas at the same height, facing each other and having clear line of sight. After this calibration, the precision and accuracy were evaluated at different distances, angles and heights between the Tx and the Rx in open space and inside a tree canopy. For the canopy experiment, a pear tree was selected. The height of the tree was 3 m; the bigger diameter of the canopy was 2.5 m.

To estimate the statistics of the error in the presence of foliage, three experiments were conducted. One RCM (#1) was placed inside the canopy at a height of 1879 mm from the ground and was kept fixed at that position. In the first experiment, a second RCM (#2) was placed at a height of 1143 mm from the ground at three horizontal positions A, B, and C, which were 1 m, 2 m and 3 m away from RCM #1 respectively. The planes of the two antennas of the two units were placed parallel to each other. In the second experiment, RCM #2 was placed at the same horizontal positions A, B and C, but this time at a height of 533 mm from the ground. In the third experiment the second experiment was repeated with the planes of the two RCM antennas perpendicular to each other, in order to assess the effects of non-uniform antenna directionality. The same sets of experiments were conducted in open space without any tree.

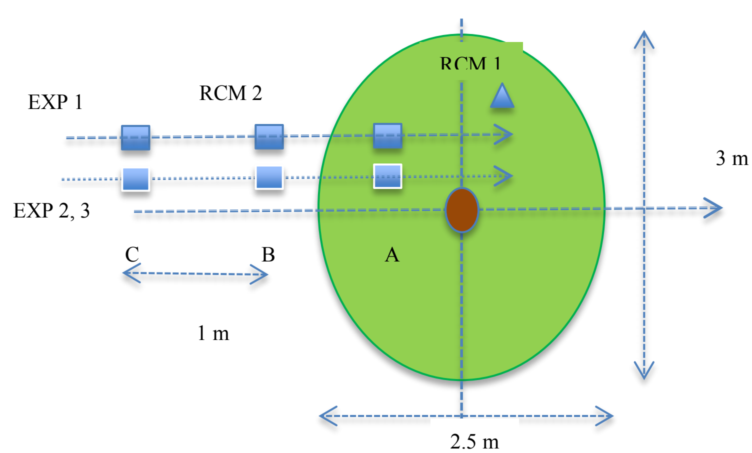


Fig. 2. RCM beacon positions and canopy dimensions; RCM #1 (triangle) and RCM #2 (rectangle).

Finally, the three experiments mentioned earlier were repeated using 3 different RCMs (#3, #4 and #5) in place of RCM (#2). Hence, a total of 12 measurement sets were recorded using four RCMs (#2, #3, #4 and #5) and RCM #1 in the tree canopy. The same sets of experiments were conducted in open space without any tree. So, a total of 24 experiments were conducted with RCM #1 in open space and in a tree canopy. The range readings from the different experiments were saved into MS Excel files using the RCM Reconfiguration and Evaluation Tool (RET); this is software provided by the RCM manufacturer. For each of the experiment 1000 readings were recorded and then the median for the consecutive 5 measurements were calculated leaving 200 readings for each experiment. The range error in the RCMs was obtained by subtracting the median of these distances from the actual distance measured using the laser. The error histograms obtained from the open space and canopy experiments were then fitted using the *dfittool* function in Matlab to obtain the non-parametric probability density functions (pdf) of the open-space and canopy errors. These error pdfs were used to evaluate the trilateration error pattern in the data collection volume.

Trilateration error estimation

The geometry of the trailer, beacons and fruit-picking workspace are shown in the next figure. The trailer moves along orchard rows having the trees to be harvested to its right. The mobile trailer is represented by the rectangle. Four RCM beacons were placed at points N (1.4, -0.02, 1.9); M (0.6, -0.02, 1.9); O (0.6, 2.3, 1.9); P (1.4, 2.3, 0.5); all coordinates are in meters, with respect to an origin frame at the upper left corner of the trailer. The dimensions of the fruit picking workspace range from -2 m to 4.8 m in Y direction, 1.8 m to 3.2 m in X direction and 0 to 4 m in Z direction.
To estimate the error introduced by the trilateration technique the following procedure was used. Let us consider a point (*x, y, z*) in the data collection volume. The beacon co-ordinates of the 4 beacons mounted on the trailer are known: ${}^{WF}\mathbf{b}_i = [bx_i\ by_i\ bz_i\ 1]^T$, i = 1…4). Hence, the distances r_1, r_2, r_3 and r_4 can be calculated using the Euclidean distance formula.

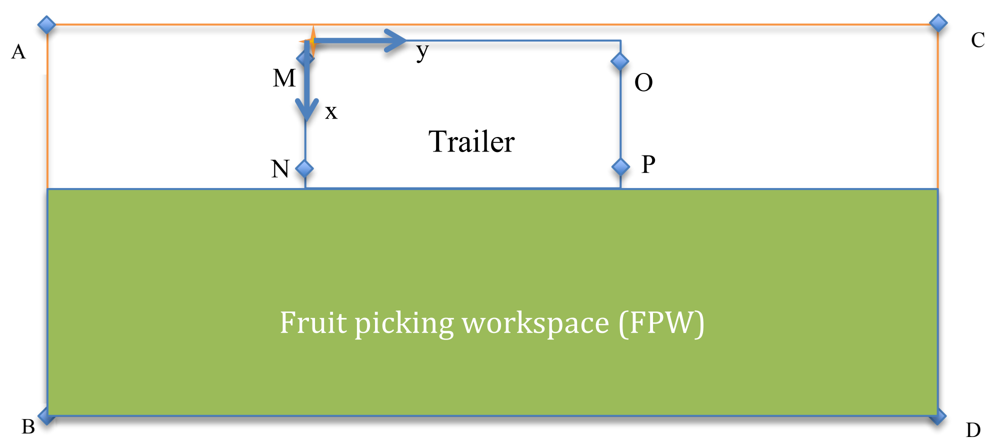


Fig. 3. Data collection volume and fruit picking workspace.

The experimentally-produced non-parametric probability density function of the range error is used to produce random samples of noise that are added to the true distances, in order to simulate the distances ($\widehat{r_1}, \widehat{r_2}, \widehat{r_3}$ and $\widehat{r_4}$) reported by the RCMs. By using these estimated distances and the beacon co-ordinates, the coordinates (x^*, y^*, z^*) of the mobile antenna are estimated using the trilateration technique as shown in the Fig. 4. The trilateration error is defined as the Euclidean distance between the true point (x, y, z) and the estimated point (x^*, y^*, z^*).

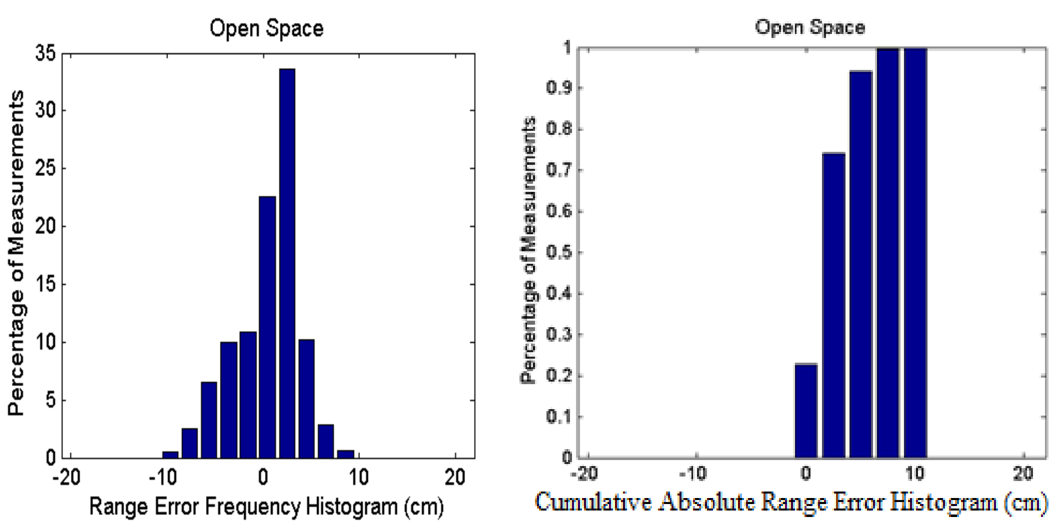
For each point (x, y, z) this procedure is repeated one thousand times to sample adequately the range error statistics. Furthermore, the errors over different heights (z=0 to z=5m with 0.5 m step) are grouped, and the average absolute error and the 95th percentile of the absolute error are reported as measures of the trilateration error at each location (x, y).

EXPERIMENTAL RESULTS

This section presents experimental results for the characterization of the antenna distance range error ε_i, the trilateration error of the coordinates (x^*, y^*, z^*), and fruit location data from an orchard.

Range error and Trilateration error

The resulting error histograms for the open space and tree canopy experiments are shown in Fig. 4.



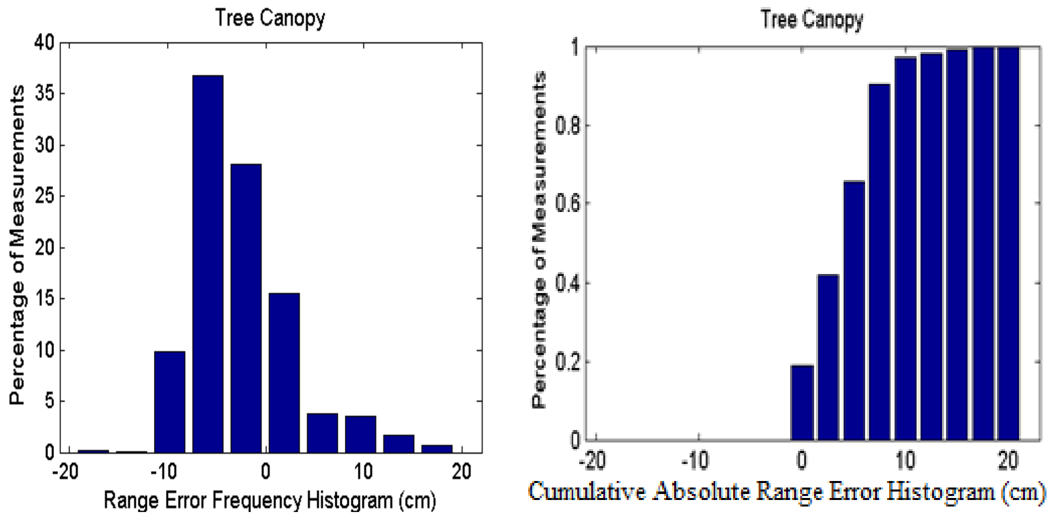


Fig. 4. Error histograms

From the results we can see that at a 90% confidence level the range error inside tree canopies is less than 8.7 cm, and in open space it is less than 5.4 cm. It is also evident that 95% of the times the range error is less than 9.5 cm for the tree canopy and 6.5 cm for the open space. The 95% error magnitude over the entire FPW workspace was calculated using trilateration error estimation procedure described in the previous section and was found to be approximately 40 cm. However, by limiting fruit picking next to the trailer region i.e., the part of FPW between lines MN and OP the 95% error magnitude is less than 20 cm.

Fruit locations

Manual fruit harvesting was performed in a pear orchard block that near Lakeport, CA, USA, located at latitude 3900.53128 N, 12250.36713 W (WGS84 geodetic datum). The trees were large open-vase hedgerow Bartlett pear trees, approximately 12 years old and 5 m high, and had not been harvested before in the season. Seven trees along a row were tagged, and each tree was given a unique identification (ID) code. A picker was instructed to pick from the tagged trees all the fruits that met the grower's size standard; he was also instructed to grasp with each hand only one fruit at a time.

The orchard block and the seven trees are shown in Fig. 5. A map of the fruit locations in 3D is shown in Fig. 6. The yield of each tree can be seen in Fig. 7.

Fig. 5.1 Data collected from seven pear trees inside the yellow rectangle.

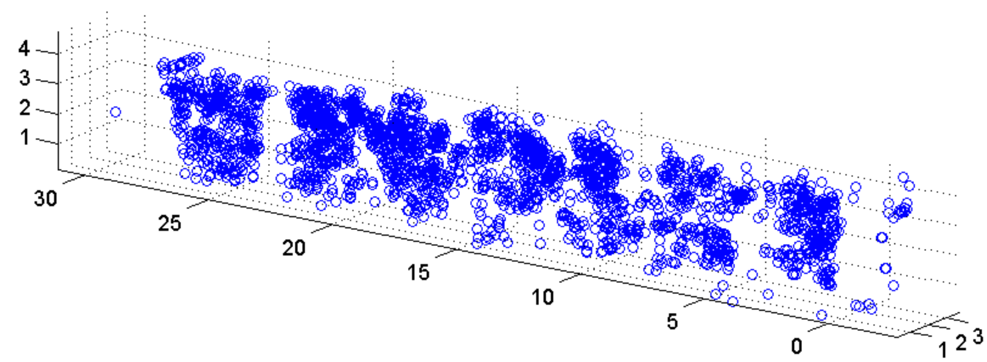


Fig. 6. Fruit locations in the canopies of seven trees in a row.

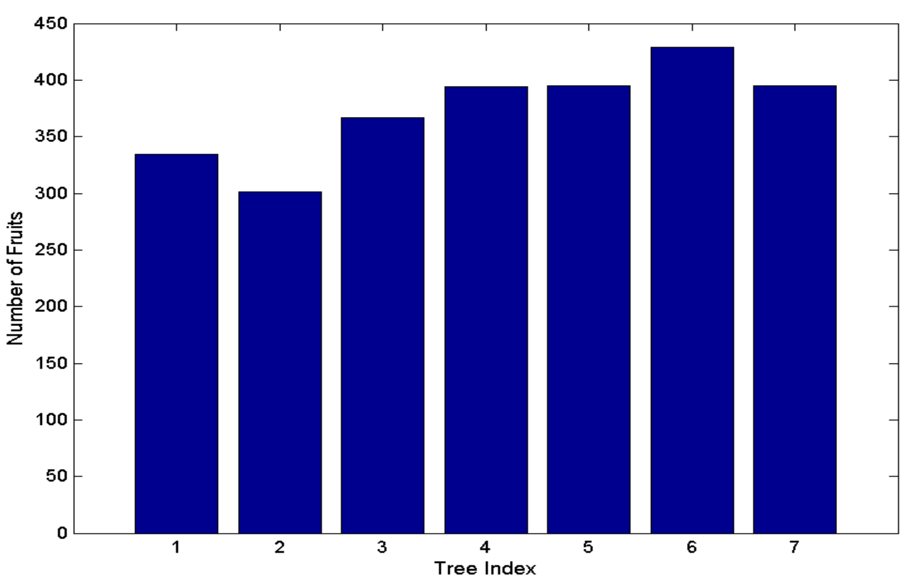
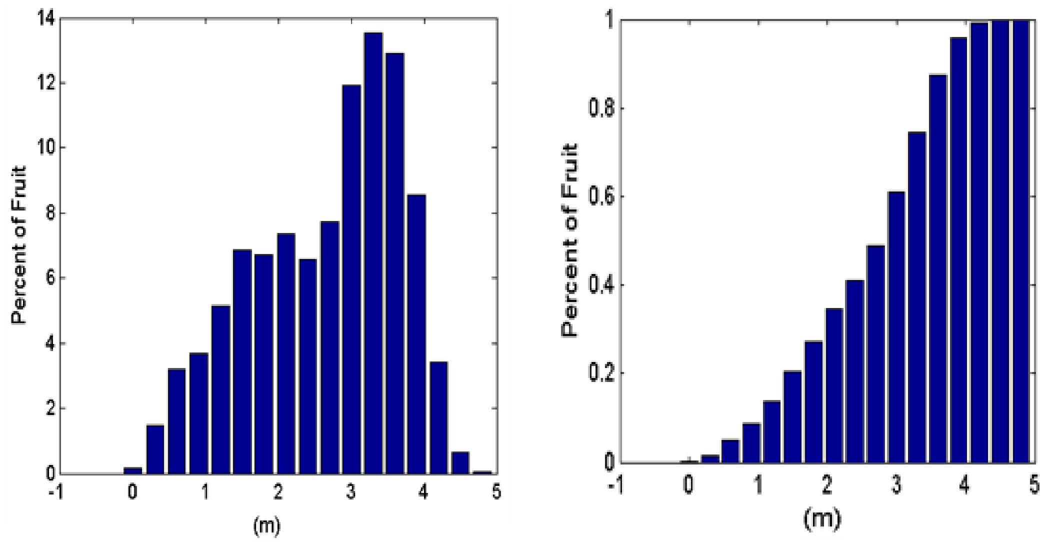


Fig. 7. 2 Number of fruits (yield) per tree.

The height distribution of the pears for the seven trees in the row is shown in the normalized histogram in 8. The mean value of this height is E(h) = 2.6 m, and the standard deviation, σ = 1 m. The corresponding cumulative height histogram is given in 8(b). It can be seen that these old trees bear fruit from near the ground to their tops. Approximately 70% of the fruit is above 1.8 m, i.e., the average picker on the ground cannot reach it.



(a) (b)

Fig. 8. (a) Fruit height normalized histogram (b) Cumulative fruit height histogram.

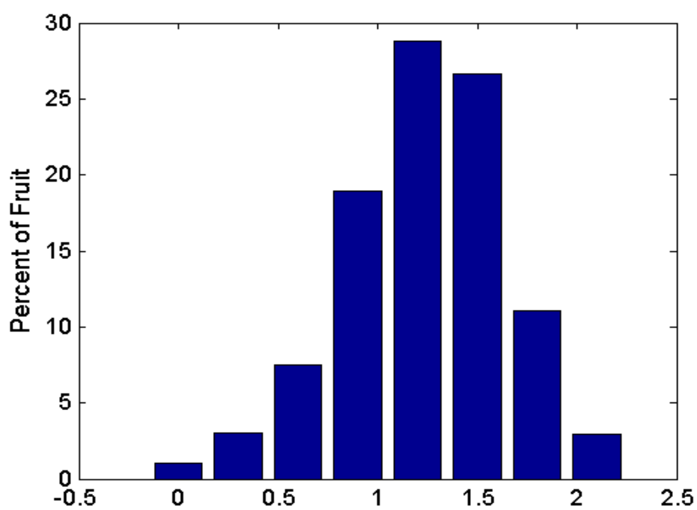


Fig. 9. Normalized histogram of fruit horizontal minimum distance (m) from the left or right row centers.

The normalized histogram of the fruit distances from the row-centers is shown in 9. The mean value of this distance is E(d) = 1.2 m, and the standard deviation, σ = 0.4 m. Trees trained in hedgerows are expected to have a smaller standard deviation than standard open-vase trees.

DISCUSSION AND CONCLUSIONS

A novel large-volume location digitizing system was presented. The 95% error magnitude in its workspace was approximately 40 cm. However, the error magnitude is not uniformly distributed over the digitizing volume. It is maximum in the rear end of the trailer and moderate in the front end of the trailer. The reason is that trilateration error is sensitive to relative geometry among the beacons; this is the well-known Dilution of Procession (DOP) error. By limiting fruit picking next to the trailer region i.e., the part of FPW between lines MN and OP the 95% error magnitude is less than 20 cm; the mean error is 11 cm. The conducted fruit location mapping experiments used this limited workspace to limit the error to less than 20 cm. The system proved practical for field use and was used to digitize 2-3 thousand fruit locations per day.

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