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Two fruit counting techniques for citrus mechanical harvesting machinery

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ARTICLE INFO

Article history:
Received 25 March 2008
Received in revised form
28 August 2008
Accepted 26 September 2008

Keywords:
Time of flight
Poisson process

ABSTRACT

Two fruit counting methods were developed for citrus mechanical harvesting machineries. The first method relied on the flow of fruits forming a random arrival process (Poisson process), whereas the second method relied on counting singulated fruits. The first approach was based on a method developed earlier targeted at measuring the flow rate and mean particle diameter of granular fertilizer particles. A similar approach was used in this research, where a large time of flight device was developed that measured the lengths of clumps of fruits falling through the time of flight device. The clump lengths were subsequently used to estimate the number of fruits passing the sensor per time unit. This method can only work accurately if the flow of fruits constitutes an independent arrival process (Poisson process). The advantage of this method is that it is non-intrusive, founded on theory and does not require calibration. However, during experiments it became evident that the flow of fruits directly after being transported from a conveyor belt was not Poisson driven, and therefore the method failed.

As an alternative, a second method was developed which did not rely on any assumptions about the flow regime and is also virtually non-intrusive. This method uses a flow separation section which funnels and singulates the flow of fruits into five channels. The fruits in these channels were counted individually using laser-based photo-interruption sensors. This method, although more rudimentary than the Poisson-based approach, yielded good accuracy: during laboratory tests, where a total of 2000 fruits passed the sensor, 1996 were counted, yielding an error of 0.2%. This result was obtained with an unrefined sensor, and further increase in accuracy may be possible. Testing is planned on a full size canopy shaker fruit harvester under field conditions to assess the robustness and to develop methods to resolve potential errors introduced by debris.

1. Introduction

Citrus fruits in Florida represent the state's most valuable agricultural product worth 742 million dollar in 2005 (Florida Agricultural Statistics Service, 2005). To date, a large percentage of fruits are still harvested by hand, but mechanization is a growing effort. Early on, there were attempts to develop fruit counting systems for manual harvesting by counting and locating containers in the field (Whitney et al., 2001; Schueller et al., 1999). Annamalai et al. (2004) used a machine vision

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doi:10.1016/j.compag.2008.09.002

approach to obtain an estimate of the yield of citrus fruits per tree.

Tree canopy shakers are a promising method of mechanically harvesting citrus fruit, but they lack a reliable method of fruit counting. Canopy shakers have a conveying mechanism that transports the fruits from the catching system upward to a level where the fruits roll along a ramp into the collection truck. A simple approach to fruit counting would now be to count every fruit that is transported into the collection truck. However, the fruits in the flow are not singulated, and therefore the system needs to be capable of either singulating the flow and count the fruits individually, or be capable of counting the fruits while they clump together. In addition, an important requirement of the proposed fruit counting systems is the absence of the need for calibration. Not only does the need for repeated calibration place an extra time burden on the grower during harvesting, in practice it will be ignored. Within the constraints and requirements, two methods of fruit counting were proposed. In the first method, the flow of fruits was regarded as a sequence of clumps and spacings, and a large time of flight device (LTFD) was developed to measure the lengths of the clumps. The LTFD consists of two horizontally oriented grids each containing 20 laser beams. These grids are interrupted by the clumps and since the grids are spaced 28 mm apart, the difference between the interruption times was used to measure the velocity of the clumps and subsequently the clump lengths. The method has the advantage of being calibration-free, non-intrusive and clog-proof but it requires an algorithm to estimate the total number of fruits from the clump length data. This algorithm is based on the assumption that the flow of fruits constitutes a random arrival (Poisson) process. Grift and Crespi (2008a,b) developed methods to measure the flow rate as well as the mean diameter of particles free falling from a funnel into a tube. They showed that the flow of particles in the fall tube indeed constitutes a Poisson process very soon after the particles leave the funnel. This same method and inherent Poisson assumption are applied in this research, albeit with a much larger time of flight device, larger particles (citrus fruits), and lower flow densities.

In the second method, the flow of fruits was divided into five channels, each of which contained a laser interruption sensor that counted the fruits. This method is also calibration-free, virtually non-intrusive and no assumptions were needed about the flow regime other than that fruits pass the sensors individually. This method is however prone to clogging under high density fruits flows, and debris may cause problems in the field as well.

The objective of this research was to develop two calibration-free fruit counting technologies for mechanically harvested citrus and to assess their feasibility and performance in a laboratory setting.

2. Materials and methods

The two proposed fruit counting methods include the development of hardware consisting of the LTFD as well as a flow separation device. Furthermore, the LTFD system relies on a mathematical foundation, which among fruit counting methods, gives a method of testing whether the Poisson assumption holds. This section describes these system components.

2.1. *Large time of flight device development*

The fruit counting method based on the Poisson arrival assumption depends on the ability to measure the lengths of the clumps of fruits in real time. For this purpose, a LTFD was developed. Fig. 1 shows a photo of the device.

The top left side of the photo shows 40 optical receivers arranged in two horizontally oriented grids containing 20 receivers each, coupled with 40 laser transmitters shown on the right. The distance between the two laser grids was not chosen but dictated by stacking of the laser transmitters, which yielded a distance of 28.0 mm. The receivers consisted of phototransistors (Ligitek LPT2023, Jameco Electronics, Belmont, CA) whose emitters were connected to ground, and whose collectors acting as outputs, were pulled up to +5 V with 100 kΩ resistors yielding active-low optical switches. The phototransistors have no electric basis, instead the photons provided by the laser transmitters enable current flow from collector to emitter. The 100 kΩ resistor choice was made to ensure that when the sensors receive the full intensity of laser light, the output is drawn close to ground level (approximately 0.5 V).

The phototransistors form two grids by connecting all 20 receivers within a grid in a logical AND function. In this way, the measurement becomes independent of the location in the horizontal plane where the fruits interrupt the grids. The inset in Fig. 1 shows typical signals that emerge when a spherical object interrupts both grids in short succession. The phase difference between the interruptions of the two grids, combined with the constant distance between these grids, enables measuring the velocity of the clumps. When this velocity is combined with the pulse width of one of the grid's signals, the clump length can be computed. The timing information was obtained from the two output signals using a counter/timer board (NI6602, National Instruments Corporation, Austin, TX) with a clock rate of 20 MHz. Fig. 2 shows the data acquisition system layout.

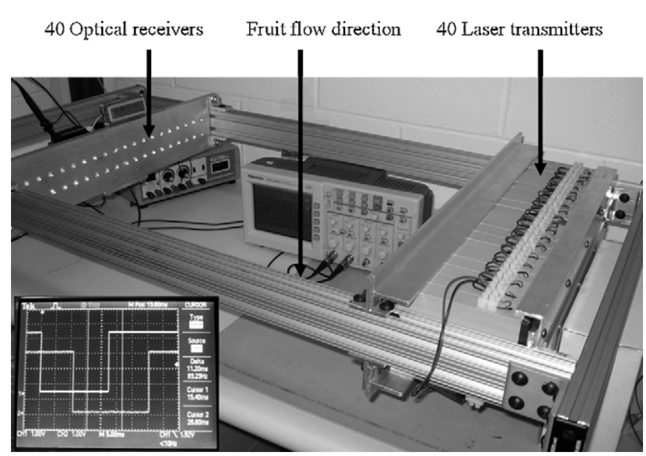

Fig. 1 – Large time of flight device (LTFD) containing 40 laser beams arranged in two rows of 20 beams. The inset originates from a single spherical object passing through the sensor grids yielding two out-of-phase signals allowing measurement of velocity and length of the fruit clumps.

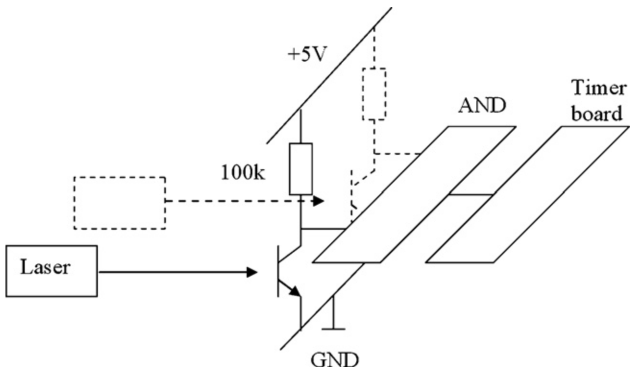

Fig. 2 – Data acquisition system of one of two grids of the large time of flight device (LTFD). 20 lasers beams (2 are drawn) are optically connected to phototransistors, which are pulled up to 5 V by 100 kΩ resistors to form active-low optical switches. All 20 laser beams are combined in a single logical AND function forming an optical interruption grid. The timer board measures the active-low pulse lengths during interruption of the grid by a fruit clump (see inset in Fig. 1).

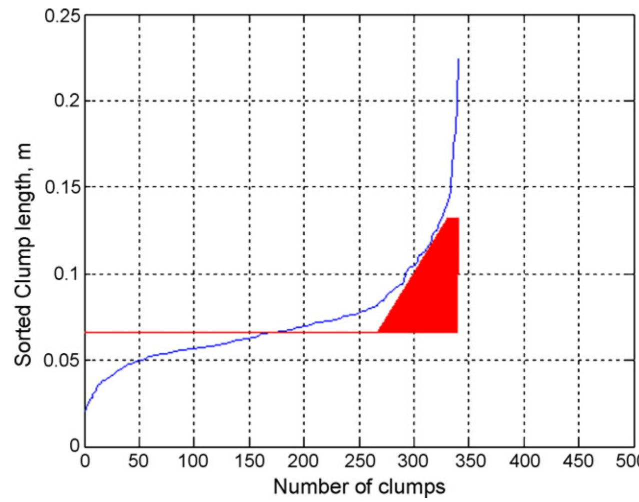

Fig. 3 – Measured sorted clump lengths (curved line) approximated by the sorted simulated identical particle clump lengths (straight lines). The break point in the straight line (at 266 clumps) indicates the estimated number of individual unclumped particles in the flow.

2.2. *Poisson-based fruit counting*

The Poisson-based fruit counting approach inherently assumes that the flow of fruits forms an intermittent succession of clumps with spacings among them. If the arrivals of the fruits at the sensor are independent and random, the process is termed a Poisson process. Such process is also known as a simple linear Boolean model and statistical estimators have been developed (Crespi and Lange, 2006). Fruit counting was here regarded as the problem of estimating the number of fruits passing a sensor per unit of time based solely on the measured lengths of the clumps they form. To test the performance of the method, experiments were carried out where the initial number of fruits N is known (typically 500 per experiment) and subsequently the measured clump lengths were used to estimate the initial number of fruits. The performance of the method is now simply a function of the numerical proximity of the estimated number of fruits to the initial number. After a successful experiment, the following data are available: (1) N_T, the counted number of clumps, which is always lower than the initial number of fruits in the experiment N, and (2) the clump lengths in m. It is also assumed that the mean fruit diameter $\bar{D}$ in m is known, either from offline measurements or by dropping a number of fruits through the sensor individually in random fashion.

To estimate the initial number of fruits in the experiment using only the clump lengths and the known mean particle diameter $\bar{D}$, a simulated identical particle approximation (SIPA) method was applied (Grift, 2003). This method approximates the clump length distribution of a flow of distributed diameter particles (which is always the case in real flows) by the simulated clump length distribution of identical particles with diameter $\bar{D}$.

After an experiment where for example 500 fruits were dropped through the sensor, the number of clumps N_T is counted. Subsequently, the obtained clump length distribution is approximated by the SIPA method which uses the known mean particle diameter $\bar{D}$ and yields an estimate for the number of single particles among the clumps N_0. Then the following equation was used to estimate the initial number of particles (500) (Grift, 2003).

$$\hat{N} = \frac{N_T^2}{N_0} \qquad (1)$$

Fig. 3 shows this process applied to data from an actual citrus fruit flow experiment.

The curved line shows the sorted measured clump lengths in blue. The mean diameter of the fruits was 66.4 mm, but the total variability in this line is caused by the true diameter variability, which was 14.7 mm, added to an average measurement error in the sensor of 5.3 mm, giving a total of 20 mm standard deviation. The total number of clumps counted here was 340. Based on the known mean fruit diameter (66.4 mm) the clumping process was simulated using identical particles (with a diameter of 66.4 mm) for increasing flow density (straight lines in red). This process was repeated until the straight lines from the simulation coincided with the measured clump lengths. This resulted in an estimated number of individual fruits N_0 among the clumps of 266. By applying Eq. (1), the estimated initial number of fruits was $\hat{N} = N_T^2/N_0 = 340^2/266 = 434$. This estimate is significantly lower than the original number of 500 fruits. The most logical reason for the discrepancy is that the underlying hypothesis of the flow constituting a Poisson process is invalid. For this reason, Section 2.3 gives a method to test this assumption.

2.3. *Test of Poisson process assumption validity*

To test if the flow indeed is Poisson driven, a straightforward method is to compare the mean of the measured clump lengths with the mean of the theoretical clump lengths for a given flow density. Some parameters are known such as the mean fruit diameter $\bar{D}$ in m, measured with a slide micrometer among 500 fruits being 66.4 mm, the initial number of particles, N, as well as the number of clumps, N_T, which is counted without error. A fundamental property of a Poisson flow is the fact that the density of the flow, λ_m, in particles per meter is equal to the reciprocal value of the mean spacing length $\overline{\mathrm{SL}}$ in m (Hall, 1988) or:

$$\lambda_m = \frac{1}{\overline{\mathrm{SL}}} \quad (2)$$

Grift and Crespi (2008b) showed that the theoretical relationship, assuming a Poisson flow, between the counted number of clumps during an experiment and the flow density can be expressed as follows:

$$N = N_T\, e^{\lambda_m \bar{D}} = N_T\, e^{(\bar{D}/\overline{\mathrm{SL}})} \quad (3)$$

where N is the initial number of particles in the experiment, $\bar{D}$ is the mean particle diameter in m, and N_T is the number of clumps counted. A problem here is that the spacing lengths were not measured during the tests and therefore the mean spacing length $\overline{\mathrm{SL}}$ was unavailable. However, Grift and Crespi (2008b) showed the theoretical validity of another equation which couples the mean spacing and mean clump lengths as follows:

$$N = N_T \left(\frac{\overline{\mathrm{CL}}}{\overline{\mathrm{SL}}} + 1 \right) \quad (4)$$

The combination of Eqs. (3) and (4) allows for the computation of the theoretical clump lengths $\overline{\mathrm{CL}}$ in m based on the known initial number of fruits, N, the counted number of clumps, N_T, and the mean fruit diameter, $\bar{D}$, in m as follows:

$$\overline{\mathrm{CL}} = \overline{\mathrm{SL}} \left(\frac{N}{N_T} - 1 \right) = \frac{\bar{D}}{\ln(N/N_T)} \left(\frac{N}{N_T} - 1 \right) \quad (5)$$

Since the initial number of fruits N is chosen (typically 500), the number of clumps among the fruits N_T is counted without error, and since the mean diameter of the fruits $\bar{D}$ was determined using offline measurements, the theoretical mean clump length $\overline{\mathrm{CL}}$ can be computed. Subsequently, the theoretical mean spacing length $\overline{\mathrm{SL}}$ is obtained by inserting the mean clump length $\overline{\mathrm{CL}}$ into Eq. (4) and solving for the mean spacing length $\overline{\mathrm{SL}}$. Finally, the flow rate λ_m can be computed by inserting the mean spacing length $\overline{\mathrm{SL}}$ in Eq. (2). Now it is possible to produce a plot where the theoretical mean clump length $\overline{\mathrm{CL}}$ in m is plotted versus the flow density λ_m in m^{-1}. This plot was used to determine whether the flow constitutes a Poisson process by comparing the theoretical and measured mean clump lengths as shown in Section 3.

2.4. *Flow separation method*

An alternative to the Poisson-based flow rate measurement is to separate the flow into channels through which only single file fruit flow is possible. An essential design criterion was that the system must be clog-proof. The flow separation device consisted of a smooth transition from a slanted plate onto which the fruits were dropped to five square channels with a width of 10 cm (Fig. 4).

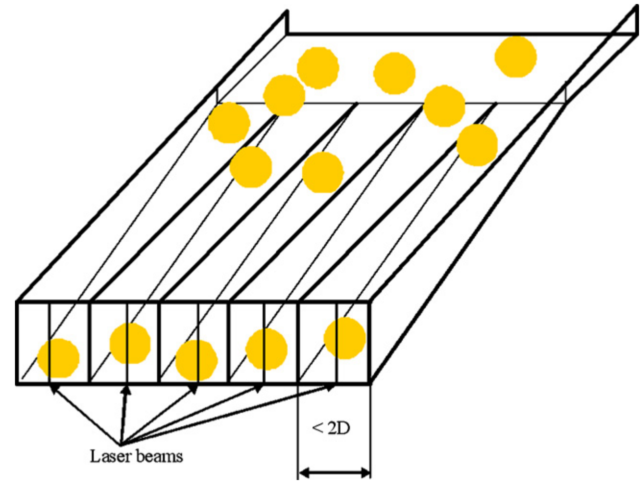

Fig. 4 – Fruit flow separation device producing five single file fruit flows. The width of the channels was chosen lower than twice the mean diameter $\bar{D}$ of the fruits to prevent simultaneous fruit passage.

At the exit point of each channel, a photo-interruption sensor is present which consists of a laser beam combined with an optical receiver. The receivers were of the same type as those used in the large time of flight device (Ligitek LPT2023, Jameco Electronics, Belmont, CA).

There are three errors anticipated in the counting process. Firstly, there is a chance of overestimation, which may be caused by multiple signal edges called 'bounces' when the laser beams are interrupted. This problem was addressed by signal debouncing using Schmitt-Trigger circuits. Secondly, there is a chance that the number of fruits is undercounted, owing to the fact that when two fruits pass the sensors simultaneously, they could be counted as one. The design of the channels is such that the probability of this event is negligible, since the channels are not wide enough for two fruits to pass each other. In addition, the ramp has a downward slope and theoretically under constant acceleration, the distance among the fruits must increase with time and distance. However, depending on the resistance that the fruits experience in the channels, combined with the chance that some fruits will bounce in the channels, there is a small chance that fruits will stack up and pass the sensors as one.

Thirdly, a potential source of error is caused by the flow of fruits containing foreign objects such as leaves, vines, twigs, bark and other debris. If these objects cover a sensor completely and continuously, the error is easily detected since the sensor output is low for a time period much longer than that related to the passage of a fruit. If a foreign object passes the sensors, it will be counted as a fruit resulting in error. However, most foreign objects have dimensions that differ significantly from the fruit dimensions, implying that their interruption times will also differ from the fruit interruption times. This difference gives a handle on how to detect this type of error. The most logical solution to the foreign object error is to prevent the objects from entering the sensor altogether

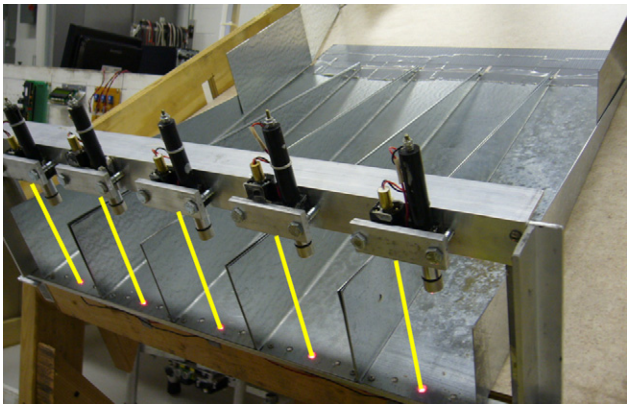

Fig. 5 – Photo of flow separation arrangement containing five channels, each with one laser-based photo-interruption device which counts fruits individually.

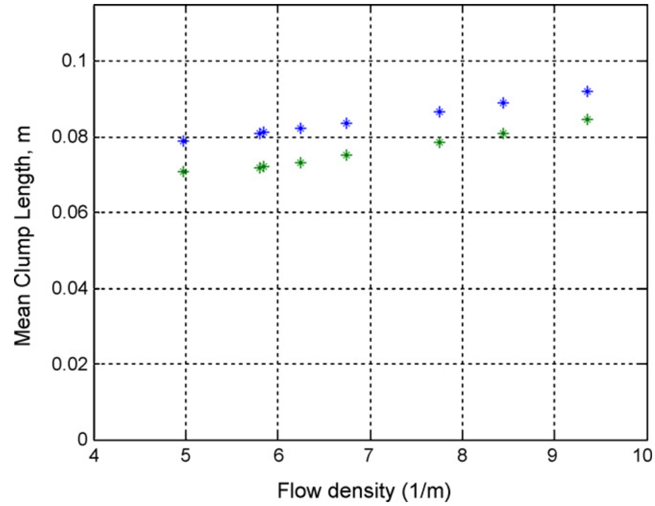

Fig. 6 – Theoretical clump lengths (upper data series) and measured clump lengths (lower data series) indicating that the flow does not constitute a Poisson process.

for instance by applying an airflow that separates the debris from the fruits. This solution was not tested and is proposed for further research. Fig. 5 shows a photo of the flow separation arrangement. The laser beams were drawn in the photo, to show their locations.

The hardware used for counting was the USB 4303 10-channel counter/timer board with a clock frequency of 20 MHz (Measurement Computing Corporation, Norton, MA). LabVIEW® software was used for the programming of the counter/timer board.

3. Results and discussion

The Poisson-based flow rate sensor was tested by dropping a spherical ball with a diameter of 60 mm a 100 times through the sensor at arbitrary locations. This allowed characterization of the true distance between the laser grids which was found to be 28.0 mm. The distribution of the measured diameters was near-Gaussian with a mean equal to the true diameter (after sensor characterization) and the standard deviation (S.D.) among the measured diameters was 5.3 mm. The variability in the measured diameter is caused by inherent errors in the sensor, such as non-exact switching behavior of the sensors, but most importantly since the laser beams do not form a continuous sensing plane but rather a discrete grid.

Subsequently, the dimensions of all 500 fruits in the experiments were measured with a slide micrometer, in the vertical and horizontal axes. The mean value in the vertical direction was 67.5 mm (S.D. = 6.12 mm) and in the horizontal direction 65.3 mm (S.D. = 6.2 mm). In the analysis, a single value was taken as the mean particle diameter of these resulting in a mean value of 66.4 mm (S.D. = 6.17 mm).

Tests were carried out where fruits were transported using a standard conveyor section of a canopy shaker harvester, and the sensor was placed at the location where under field conditions, the fruits free fall into a truck. Table 1 shows the results among eight tests.

The errors in the estimations are obviously too high to serve as realistic measures for fruit count. To investigate the reason behind the undercounting, the question was asked whether the flow indeed constitutes a Poisson process. This question was answered by following the procedure as outlined in Section 2.3. Fig. 6 shows the theoretical mean clump lengths (from Eq. (5)) as well as the measured mean clump lengths versus the flow density in particle per meter.

The flow density values were obtained by taking the reciprocal value of the theoretical mean spacing length from Eq. (2). Fig. 6 shows a significant deviation between the measured and theoretical clump lengths among all flow densities. This is a direct indication that the flow is not Poisson driven, and therefore errors in the measurements can be expected. In theory it

Table 1 – Estimated number of fruits using the SIPA method, compared to the initial number of fruits with errors.

	Initial number of fruits	Estimated number of fruits	Error (%)	Flow density (m^{-1})
1	500	432	13.6	4.98
2	500	434	13.2	5.81
3	500	401	19.8	6.25
4	500	425	15	5.85
5	496	400	19.35	8.45
6	490	416	15.1	6.75
7	488	430	11.89	9.36
8	484	389	19.63	7.76

is possible to calibrate the sensor by relating the measured and theoretical data presented in Fig. 6, however, firstly, a requirement was the sensor being calibration-free, and secondly, even though calibration may work for this pseudo-Poisson flow regime, in reality the sensor would have to be recalibrated when the proximity to a Poisson flow changes, an effect which is unobserved. Therefore the method as proposed here was deemed unfit for fruit counting, not because of the sensor itself, but since the flow is not Poisson driven.

Even though the flow separation method was more rudimentary than the Poisson-based method, it yielded superior results. The main reason is that after singulation using the flow separator, the counting process was simple and straightforward. The method was tested by running 50 tennis balls at once through the sensor, without under or overestimating once among 20 replications. No clogging occurred. Subsequently, oranges were dumped onto the ramp in batches of 50. This procedure was repeated 40 times, and the number of fruits counted. Again, no clogging of the flow was encountered. The total number of fruits counted was 1996 out of 2000, which indicates an error of 0.2%. The mean count per experiment was 49.9 out of 50 and the standard deviation per batch was 0.778. Among 40 experiments, 1 led to a count of 48, 9 led to a count of 49, 25 led to a count of 50, 3 led to 51 and 2 led to 52. The maximum deviation from the original 50 count was 2, or 4%.

A comparison between the tennis ball tests where no errors were encountered, and the citrus fruit experiments which showed some erroneous counts, indicates that the fruits themselves cause errors. The most likely cause for these errors is the non-spherical and partially concave shape of the fruits. It must be noted that the flow separation counter is unrefined, and optimization may be possible for instance by monitoring the electrical pulse lengths to detect switch bouncing. This may become important when the system is applied on a vibrating machine which most likely will cause more error.

4. Conclusions

Two methods to measure the instantaneous flow rate of citrus fruits per time unit were devised: (1) a large time of flight device which used Poisson theory for data analysis, and (2) a five channel flow separation unit containing one laser-based photo-interruption sensor per channel.

The large time of flight device worked properly, but the fruits were not counted accurately. The conclusion was that the flow did not constitute a Poisson arrival process and therefore the flow measurement failed.

The flow separation device showed accurate and reliable under laboratory conditions. The flow separation unit itself was designed such that it splits the initial flow into five single file fruit flows in the channels without clogging. Although much simpler than the Poisson-based approach, it counted the fruits in the channels with an accuracy of 1996 fruits out of 2000, or with an error of 0.2%. Further field testing is needed to ensure that the latter method is feasible under the strong vibrations and environmental conditions in which the citrus canopy shakers operate. In addition, the method as proposed is sensitive to debris and plant material which needs to be taken into account.

Appendix A. Nomenclature

$\overline{CL}$	mean of theoretical clump lengths in experiment (m)
$\overline{SL}$	mean of theoretical spacing lengths in experiment (m)
$\bar{D}$	mean diameter of fruits in experiment (m)
λ_m	flow density (m^{-1})
N	initial number of fruits in experiment
$\hat{N}$	estimator for initial number of fruits in experiment
N_T	number of counted clumps in experiment
N_0	number of individual fruits encountered in experiment

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