Pre-commercial sorting line for peaches firmness assessment

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Received 22 August 2006; received in revised form 27 November 2006; accepted 4 January 2007

Available online 26 January 2007

Abstract

In the fruit and vegetable sector, the demand of quality has become an important demand for consumers. Whereas first requirement sheets mainly dealt with the visual aspect, currently there is an increasing interest in other quality features, such as maturity. Maturity can be assessed by measuring firmness and sugar content. Through contract CRAFT-1999-70106, funded by the European Union, the Instituto Valenciano de Investigaciones Agrarias (IVIA) has designed a firmness sensor capable of classifying peaches in three categories: very firm, firm and not firm. This paper describes the developed sensor which is based on the analysis of fruit impact on a load cell (curve of force vs time) and its integration in a pre-commercial sorting line. The repeatability tests have demonstrated that the firmness sensor can work appropriately at a speed of 8 fruits s⁻¹ and the sensor is able to classify peaches according to their firmness with 80% repeatability.

Keywords: Sensor; Hardness; Real-time; Reliability; Repeatability

1. Industrial measurement of firmness

Appearance and texture of fruit are the two most important quality features used by the consumers to choose peaches. Although the parameters describing the appearance of fruit (colour, size, presence of defects) can be measured in physical terms, texture is a sensation related to different experiences produced during eating a food or during its handling. For this reason, instruments are only able to measure some texture characteristics, but not the sensorial attributes of texture. The importance of texture in global quality is highlighted when it is considered one of the decisive sensorial attribute in which the consumers base their subjective decision of buying some fruit species, for instance melons, peaches and, in certain cases, pears and apples. These fruits are tested by the consumer through the production of an imperceptible deformation as they press gently the fruit and they will not accept any fruit with a particular deformation characteristic, which is what we refer to “firmness”. Firmness is relevant to the consumer because it refers to the consistency and texture of fruits, and for the relationship it may have with fruit maturity.

Firmness not only might be a reasonable estimation of maturity, but it is also related with shelf-life, because the firmness of a fruit decreases gradually as it becomes more mature and rapidly as it ripens. This perception is also employed to estimate if the fruit has undergone any kind of physical damage.

Traditional methods of firmness estimation are based on destructive tests. The most extended method is the Magness–Taylor test (Magness & Taylor, 1925) based on the resistance to penetration of a cylindrical device in the fruit flesh. Other attempts to substitute this test have been carried out by Studman and Boyd (1994). Because both methods are destructive, they can not be performed on every fruit, and are used as a rough estimation of the firmness of a fruit consignment.

Fruits can be modelled as visco-elastic spheres. The reaction force when hitting a rigid surface depends strongly on the Poisson’s ratio, the elastic modulus (which is related with firmness), curvature, mass and velocity. Fruits less...
mature are more elastic, and viscosity grows with level of maturity (García, Ruiz, & Chen, 1988).

Several non-destructive methods for firmness estimation have been developed; the most important ones are based on vibrations (Abbott, Massie, Upchurch, & Hruschka, 1995), ultrasounds (Galili, Mizrach, & Rosenhouse, 1993), compression (Bellon et al., 1993) and impact forces.

Basically, impact methods deal with the free fall of the fruit over a force sensor and analyse its response over the time of contact. The most obvious way of understanding the principle of these sensors is that the “harder” the fruit is, the stronger should be the impact, and the time of contact with the sensor should be shorter. Several examples can be found in the literature (Chen & Ruiz, 1996; De Baerdemaeker, Lemaitre, & Meire, 1982; Delwiche, Mcdonald, & Bowers, 1987; Homer, Ortiz, Moreda, Morabito, & Ruiz, 2002; Rohrbach, Franke, & Willits, 1982; Zhang, Stone, Chen, Maness, & Brusewitz, 1994).

Through contract CRAFT-1999-70106, funded by the European Union, the Instituto Valenciano de Investigaciones Agrarias (IVIA) has designed a firmness sensor capable of classifying peaches in three categories: very firm, firm and not firm. Two objectives were considered in this work:

(i) Development of a firmness sensor prototype based on a load cell: parameters selection from the force–time curve;
(ii) Integration of the sensor in a pre-commercial sorting line: establishment of the maximum working speed and sensor reliability.

2. Firmness sensor prototype

2.1. Description of the sensor

The firmness sensor prototype developed by the IVIA (Fig. 1), is based on the study of the impact of the fruit on a load cell.

The fruit is situated on a folding platform by means of a controllable electromagnetic device from the PC. The fruit will fall freely on a load cell, from a constant height that can be set from 1 to 6 cm. The surface that receives the impact of the fruit is polymethylmethacrylate consisted in thermoplastic polymer. Previous studies carried out in the IVIA (Pons, 2000) assured that the impact does not damage the fruit. It can be considered that the fruit receives two major impacts (one produced by the direct fall from the platform and the second due to the first rebound).

The load cell is a transducer that generates an analogical signal that is proportional to the applied force. Its signal is acquired by a PC through an acquisition board. At the end of the measurement, a curve of evolution of the force \( F \) versus the time \( t \) is obtained.

2.2. Parameters obtained with the sensor

Once the impact (force as a function of time) is recorded (Fig. 2) several parameters are calculated from the obtained signal to extract the most relevant information.

The fall of the fruit on the load cell produces a force that causes a deformation on its flesh. The fall on the load cell represents, evidently, an inelastic shock, during which there is a transmission of a certain fraction of the total energy of fruit. After the first impact, the fruit suffers a second impact...
due to the rebound and a new transmission of energy is produced. These energy fractions are directly related with the firmness. For this reason, we can suggest a parameter of the curve directly related with this phenomenon, which should be independent of the mass of the fruit: the relationship between the width of the first impact, \( a_1 \), and the achieved maximum force, \( p_1 \). This parameter is defined by \( p_1/a_1 \).

Following this reasoning, the second impact will be strongly influenced by the state of firmness of the fruit, because it is related to the energy that still contains the fruit after the first impact. For these reasons the following parameters are also proposed:

(i) \( a_1 \), the width of the first impact;
(ii) \( a_2 \), the width of the second impact;
(iii) \( p_2/a_2 \), the relationship between the maximum force during the second impact, \( p_2 \), and its width;
(iv) \( p_2/p_1 \), the relationship between the two maximum forces related to the energy transmissions;
(v) \( a_2/a_1 \), the relationship between the widths.

On the other hand, previous studies carried out by IVIA (Gutierrez, Ramos, & Moltó, 1999) and other authors (Delwiche, 1987; Rachmani, Schmulevich, & Edan, 1994; Rohrbach et al., 1982), have shown good correlations between the state of firmness of fruit and the relationship among the maximum taken place during the impact \( p_1 \) and \( p_2 \) and the square of the time at which it was produced \( t_1 \) and \( t_2 \). Therefore, two more parameters are proposed: \( p_1/t_1 \) and \( p_2/t_2 \).

Other parameters to be extracted from the impact curve are:

(i) \( p_1^2/m \), square of the maximum force of the first impact divided by the mass of the fruit;
(ii) \( p_2^2/m \), square of the maximum forces of the second impact divided by the mass of the fruit;
(iii) \( m/t_1^2 \), mass of the fruit divided by the square of the time in which the maximum is reached (first impact);
(iv) \( m/t_2^2 \), mass of the fruit divided by the square of the time in which the maximum is reached (second impact).

With the objective of selecting, from all previously mentioned parameters, those more reliable, an experiment has been carried out with the sensor prototype using a rubber ball. The experiment consisted of dropping 60 times a rubber ball with weight of 111 g in three non-consecutive days. After calculating the parameters of the curves the variation coefficient of each one of them was obtained.

Table 1 shows the results of first experiment with sensor prototype using the rubber ball, aimed to study the reproducibility of the selected parameters.

As seen, the parameters with good reproducibility (coefficient of variation <0.05) are: \( a_1 \), \( a_2 \), \( p_1^2/m \), \( m/t_1^2 \), \( p_1/a_1 \) and \( a_2/a_1 \).

2.3. Firmness reference

A reliable firmness reference is necessary to establish a relationship with the parameters extracted from the force–time curve. Thus, destructive measurements have been made using a universal testing machine (Instron 4301). The tests have been normalised and were based on the Magness–Taylor procedure. They consist on the penetration of the peach pulp, without skin, using a cylinder with a diameter of 8 mm. Two measurements were taken, each on equatorial zones of the fruit, separated by an angle of approximately 90°. The penetration speed was 10 mm min\(^{-1}\). The following parameters were recorded:

(i) maximum penetration force, expressed in N;
(ii) maximum penetration of the cylinder, expressed in mm.

Hardness, defined as the ratio between maximum force and maximum penetration, expressed in N mm\(^{-1}\), has been chosen as firmness reference.

2.4. Discrimination power of the selected parameters

An experiment was designed to estimate the firmness reference with selected parameters and to compare the classification of peaches using the reference and the classification obtained with sensor measurements. For this experiment 250 peaches were purchased in a local market from two soft flesh varieties (Ryan Sun and O’Henry) and two hard flesh varieties (Sudanell and Miraflores), making a total of 1000 fruits. Non-destructive, immediately followed by destructive measurements (hardness and sugar content) were carried out on each of these varieties along four weeks, employing this scheme:

(i) 1st week: 100 peaches were tested the same day that they were acquired;
(ii) 2nd week: 50 peaches were tested after being stored for 1 week;

Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Coefficient of variation, CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>0.008</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>0.046</td>
</tr>
<tr>
<td>( p_1^2/m )</td>
<td>0.021</td>
</tr>
<tr>
<td>( p_2^2/m )</td>
<td>0.155</td>
</tr>
<tr>
<td>( m/t_1^2 )</td>
<td>0.149</td>
</tr>
<tr>
<td>( m/t_2^2 )</td>
<td>0.047</td>
</tr>
<tr>
<td>( p_1/a_1 )</td>
<td>0.008</td>
</tr>
<tr>
<td>( p_2/a_2 )</td>
<td>0.119</td>
</tr>
<tr>
<td>( p_1/t_1 )</td>
<td>0.148</td>
</tr>
<tr>
<td>( p_2/t_2 )</td>
<td>0.097</td>
</tr>
<tr>
<td>( p_1/a_1 )</td>
<td>0.087</td>
</tr>
<tr>
<td>( a_2/a_1 )</td>
<td>0.043</td>
</tr>
</tbody>
</table>

(iii) 3rd week: 50 peaches were tested after being stored for 2 weeks;
(iv) 4th week: 50 peaches tested after being stored for 3 weeks.

The peaches were stored in a cool chamber at 4 °C and 85% of relative humidity.

A multiple linear regression analysis (MLR) was used with these variables in order to estimate the hardness of the four varieties of peaches, Ryan Sun, O’Henry, Sudanell and Miraflores.

After the analysis, parameter \( a_2 \) was discarded due to its low contribution to firmness prediction.

Table 2 shows the results of the MLR analysis for varieties Ryan Sun (RS), Sudanell (SN), O’Henry (OH) and Miraflores (MF) where the ranges of hardness variability were \((2500, 7500) \text{ N m}^{-1}\), \((2800, 4700) \text{ N m}^{-1}\), \((1600, 3500) \text{ N m}^{-1}\) and \((3400, 4200) \text{ N m}^{-1}\) for RS, SN, OH and MF varieties, respectively.

Linear behavior is observed in Ryan Sun, Sudanell and Miraflores varieties after studying plots of predicted against observed values. Besides, it has been verified that the model presents a normal distribution of the residuals for the three varieties. A possible quadratic trend is observed in variety O’Henry. Indeed, better results of regression are obtained considering this fact: \( R^2 = 0.6374 \) and \( SE = 810 \text{ N m}^{-1}\).

Low \( R^2 \) values are observed in variety Miraflores. They can be due to the existence of a great quantity of fruits with irregular shape that caused distortions in the impact curves provided by the sensor.

Another way of assessing the quality of the measurements obtained with the sensor consists in comparing their performance in classifying peaches with the performance of reference measurement. It is possible to find in the bibliography (Lleó, Valero, & Ruiz, 1999) two criteria for peach classification according to their firmness:

1. Depending on their estimated taste: peaches have acceptable taste when Magnes-Taylor force (MT) is less than 9 kg cm\(^{-2}\) and have more than 11° Brix, they have an excellent taste when MT < 10 kg cm\(^{-2}\) and have more than 12° Brix.
2. Classify peaches in two categories: not very firm (MT < 91.4 N cm\(^{-2}\)) and very firm (MT > 91.4 N cm\(^{-2}\))

Table 3 shows the classification matrix obtained with the validation set for all studied varieties. The percentage of correct classifications obtained in the experiments is bigger than 75% for all varieties.

If we consider the criterion (2), the percentages of correct classification are bigger than 60% for all varieties, as shown in Table 4.

Hardness and selected parameters of the impact curve employed to calculate the regression model have a good discrimination power when classifying peaches in the above defined firmness levels.

3. Integration of the firmness sensor in a pre-commercial machine

3.1. Description of the sorting line

After the validation of the prototype, the sensor has been integrated in a pre-commercial sorting line provided by the company FOMESA (Valencia, Spain) and showed in Fig. 3.

Linear discriminant analysis was employed for constructing classification models using half of cases. The other half of peaches was used to validate the model.

When employing the criteria of classification (1), the following parameters of the impact curve were considered as independent variables: \( a_1, \left( \frac{\rho_1^2}{m} \right), \left( \frac{m}{\rho_2^2} \right) \) and \( p_1/a_1 \). The observed sugar content was also included in the study.

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<table>
<thead>
<tr>
<th>Variety</th>
<th>Observed class</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan Sun</td>
<td>Acceptable</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>96</td>
</tr>
<tr>
<td>Sudanell</td>
<td>Acceptable</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>96</td>
</tr>
<tr>
<td>O’Henry</td>
<td>Acceptable</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>84</td>
</tr>
<tr>
<td>Miraflores</td>
<td>Acceptable</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>92</td>
</tr>
</tbody>
</table>

Independent variables: \( a_1, \left( \frac{\rho_1^2}{m} \right), \left( \frac{m}{\rho_2^2} \right), (p_1/a_1) \) and sugar content.

Table 4

<table>
<thead>
<tr>
<th>Variety</th>
<th>Observed class</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryan Sun</td>
<td>Not very firm</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>Very firm</td>
<td>85</td>
</tr>
<tr>
<td>Sudanell</td>
<td>Not very firm</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>Very firm</td>
<td>68</td>
</tr>
<tr>
<td>O’Henry</td>
<td>Not very firm</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>Very firm</td>
<td>63</td>
</tr>
<tr>
<td>Miraflores</td>
<td>Not very firm</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Very firm</td>
<td>64</td>
</tr>
</tbody>
</table>

Independent variables: \( a_1, \left( \frac{\rho_1^2}{m} \right), \left( \frac{m}{\rho_2^2} \right), (p_1/a_1) \).
The line is composed by two lanes and contains load cells to weight the fruit, a machine vision system to measure size and colour of fruit and a sugar content sensor furnished by CEMAGREF (Institut de Recherche pour l'Ingénierie de l'Agriculture et de l'Environnement, Montpellier, France) and the company PELLENC (Pertuis, France).

A specific communication protocol was developed to exchange information between subsystems and control unit, which processes data and commands the actions needed to sort fruit in categories. The protocol was implemented on the standard RS-232-C interface of the different computers connected through optical fiber.

All the devices worked synchronously, since the fruit is identified and travels on a cup, except for the firmness sensor, as in this case the fruit suffers a free fall during the impact and is later received by a cup (Fig. 4). For this reason, no loss of the fruit is allowed; otherwise the Control Unit would assign the firmness measurement of a fruit to the following one.

3.2. Intensive tests of the pre-commercial sorting line

The pilot line has been tested to estimate its reliability through continuous operation during more than two days and no more than two breaks per day. For these experiments two varieties of peaches (Spring Crest and Pavía) and a variety of nectarines (Caldesi-2000) were used.

As mentioned before, the Control Unit of sorting line receives information of all fruits from the firmness sensor. Detection of all fruit by the sensor is crucial, even in the cases in which the device could not estimate the firmness of the fruit, because at this point there was no synchronism with the rest of the machine (the fruit is not travelling on a cup).

False readings in more than 6000 impacts were about 1%. The causes and distribution of these false readings,
after the analysis of the respective impact curves, previously stored in the computer during on-line operation, were:

(i) 75% due to multiple rebounds of the fruit on sensor;
(ii) 25% due to incomplete recording of the impact curve.

The first cause of false readings can be avoided by a more sophisticated analysis of the signal, in which some pre-processing can allow the identification of the two consecutive impacts and the calculation of impact parameters in the first one alone. The second cause only can be avoided by mechanically redesigning this module, smoothing the falling of fruit and making more uniform the time consumed by the fruit since falling until impact with the load cell.

3.3. Repeatability of the firmness module

Reproducibility tests were performed to the sorting machine to estimate the repeatability of firmness module integrated in it. Two varieties of peaches (Spring Crest and Paviá) and a variety of nectarines (Caldesi-2000) were used.

Previously, the calibration of firmness sensor required a set of thirty peaches with a range of variability of hardness between 5000 and 10,000 N m\(^{-1}\). Destructive and non-destructive measures were performed on each fruit and a regression model was built to estimate the firmness of fruit. The model was validated along the intensive testing of the machine on three varieties of peaches measured in different days.

Repeatability of the firmness module was assessed by conducting tests on peach batches containing 100 fruits. Initially, the fruit was automatically sorted by the machine, working at 8 fruit s\(^{-1}\), in three classes:

(i) very firm: hardness >9000 N m\(^{-1}\);
(ii) firm: 5000 N m\(^{-1}\) < hardness < 9000 N m\(^{-1}\);
(iii) not firm: hardness <5000 N m\(^{-1}\).

These fruits were stored in three different tagged boxes. Each box was separately input again in the machine and the new classification of the fruit was recorded. Three repeatability tests were performed at random time during the intensive testing of each variety.

Destructive measurements (reference) were carried out during tests on random samples after passing through the machine.

Repeatability tests with the sorting line were carried out with random samples during the intensive tests. Table 5 shows the results obtained with the firmness sensor for all peach varieties employed (Paviá, Spring Crest and Caldesi-2000). Fruits classified in the same class in the two consecutive passes were considered as correct, and fruits classified by the system in two different classes were considered as error.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Test % Correct</th>
<th>Predicted class (% correct)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Not very firm</td>
<td>Firm</td>
</tr>
<tr>
<td>Paviá</td>
<td>1 88</td>
<td>90</td>
</tr>
<tr>
<td>2 75</td>
<td>82</td>
<td>70</td>
</tr>
<tr>
<td>3 79</td>
<td>82</td>
<td>76</td>
</tr>
<tr>
<td>Caldesi-2000</td>
<td>1 77</td>
<td>79</td>
</tr>
<tr>
<td>2 84</td>
<td>84</td>
<td>81</td>
</tr>
<tr>
<td>3 78</td>
<td>82</td>
<td>74</td>
</tr>
<tr>
<td>Spring crest</td>
<td>1 84</td>
<td>88</td>
</tr>
<tr>
<td>2 80</td>
<td>82</td>
<td>78</td>
</tr>
<tr>
<td>3 88</td>
<td>91</td>
<td>86</td>
</tr>
</tbody>
</table>

Regarding reproducibility levels, the firmness module showed an 81% of global success to classify a fruit in the same maturity state when tested twice. Very similar results are obtained on each variety.

A closer analysis of error causes showed that 56.6% of bad sorted fruit were due to corresponding hardness values that were very close to the border between two categories. 36.6% of errors were due to inhomogeneous firmness along the surface of peach. Finally, 6.8% of bad classified fruit showed simultaneously the two phenomena.

4. Conclusions

After a study on the discrimination power of the parameters obtained with the developed sensor, the four most reliable ones have been selected. Subsequently, two classifiers based on linear discriminant analysis have been proposed and tested on three varieties of peaches providing adequate results for commercial applications (75% success ratio). Moreover, when developing a multiple linear regression model to relate the parameter hardness, which is an estimate of firmness, with the four above mentioned parameters, promising \(R^2\) have been obtained.

For these reasons, a module composed by two sensors has been integrated in a pre-commercial sorting line. The intensive testing of the firmness module with two varieties of peaches and one of nectarines during three consecutive days, working at 8 fruits s\(^{-1}\), demonstrated its robustness. Besides, repeatability tests showed that the module is capable of classifying peaches in three firmness categories (very firm, firm and not firm) with an 81% success.

This study has demonstrated the possibility of constructing a commercial sorting line for classifying peaches and nectarines according to their firmness.

Acknowledgements

Authors thank the European Commission and the Spanish Ministry of Science and Technology for partially funding this work through the contract CRAFT QLK1-2000-70106 and the Project SC00-094, respectively.
References


