

Implementation of a wireless instrumented sphere for fruit processing

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Abstract – The aim of this study was to implement a wireless instrumented sphere to study the critical points in a citrus packing line by real-time measuring the impacts experienced by fruits. The non-commercial device was based on a MEMS (micro-electro-mechanical system) sensor node with a sensing range from ± 1 g to ± 400 g ($g = 9.8 \text{ m s}^{-2}$), a ferroelectric RAM (FRAM) memory, a radio frequency (RF) transmitter, a microcontroller, and a 75 mAh lithium battery. The sensor node was placed inside an appropriate case with a total weight of 100 g to represent a ‘Tardivo di Ciaculli’ mandarin. An FR receiver allowed real-time transmission of the measured data. Total acceleration values, representing the stresses experienced by fruit, were studied. The results showed that total acceleration remained below 20 g in most of the measurements, but considerably higher values, up to 80 g, were obtained between the brushing and waxing machines.

I. INTRODUCTION

Many electronic devices, also called electronic fruits or pseudo-fruits, have been developed in recent years to detect and evaluate the impacts experienced by fruits during post-harvest operations. In particular, since the 1980s, many studies have been carried out using commercial instrumented spheres. They are artificial fruits equipped with sensors that provide direct measurement of the impacts occurring during produce handling [1]. These artificial fruits typically include a triaxial accelerometer, a central processing unit, data storage, and a rechargeable power supply.

The IS100 instrumented sphere is the most used till today to test fruit behavior in post harvest handling. It was developed at Michigan State University and manufactured by Techmark, Inc. [2]. It provides data on peak acceleration (i.e., the maximum acceleration value for each impact; ± 500 g maximum amplitude) and velocity change (acceleration integrated over time). It was designed to be applied in potato handling chains [3] and then used in orange packing systems [4-6].

The PTR 200 (manufactured by SM Engineering, Denmark) is another electronic device designed for potatoes, tested by Van Canneyt et al. [7]. The impact data obtained from the so called “electronic potatoes” [8] was able to detect transfer points susceptible to cause damage to the potatoes in some packing centers.

Recently, a miniature berry impact recording device (BIRD) was developed to measure the mechanical impact on small fruits such as blueberries [9], which is important for harvesting operations [10] and post-harvesting handling.

A wireless instrumented sphere of 63 mm diameter and 160 g weight and a graphical user interface (GUI) was developed by Roa et al. [11] and tested in an orange packing system with the aim of performing real-time analysis of acceleration data. It was also applied on apple packinghouses, determining that the orange packing line had higher acceleration range peaks than the apple ones [12].

Till today, these are the only studies where a wireless device is used to analyze acceleration data in a fruit packing system.

Based on the above, the aim of this study was to develop and test a wireless instrumented sphere to study the eventual critical points in fruit packing lines by measuring the impacts experienced by fruits in real-time and visualizing them with dedicated software. It is a non-commercial prototype tested in a citrus fruit packing line in Italy during mandarin processing.

II. MATERIALS AND METHODS

The wireless instrumented sphere consists of a micro-electro-mechanical system (MEMS) sensor node (H3LIS331DL, STMicroelectronics, Geneva, Switzerland) with a sensing range from ± 1 g to ± 400 g, a ferroelectric RAM (FRAM) able to store up to 20,000 acquisitions, an RF transmitter with amplitude modulation at 433.92 MHz and 5 mW power (TX RADIO), a microcontroller (μC), a 3.7 V lithium polymer battery with a capacity of 75 mAh (BATT), two LEDs indicating that the device is operating (LED1 and LED2),

and a switch (SW). The 75 mAh lithium battery can be recharged by the PC, placing the device in “charge” mode (Fig. 1).



Fig. 1. Device in “charge” mode.

The sensor node was positioned inside a plastic ellipsoid case with its principal semi-axes equal to $a = 36$ mm, $b = 40$ mm, and $c = 23$ mm (Fig. 2) and with a total weight of 100 g to represent a ‘Tardivo di Ciaculli’ mandarin. The case was filled with foam rubber to hold the sensor node in position. A 433.92 MHz radio receiver was positioned near the packing line.

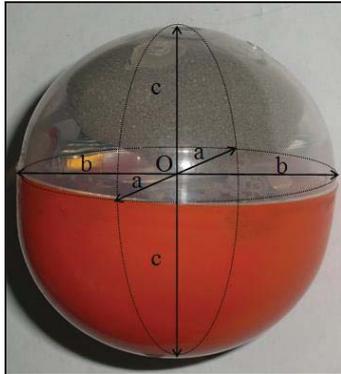


Fig. 2. Wireless instrumented sphere used for tests.

The test was performed in the ‘Tardivo di Ciaculli’ mandarin consortium (Palermo, Italy). The “Tardivo di Ciaculli” mandarin belongs to the family Rutaceae, species *Citrus reticulata*. It comes from an Avana mandarin spontaneous bud mutation and is a late-ripening variety (January to March).

The citrus packing line, with a capacity of $4 \text{ t} \cdot \text{h}^{-1}$, was divided into sections corresponding to the different processing steps [13] to evaluate the stresses experienced by the fruits during processing. Figure 3 shows the packing line plan layout.

The wireless instrumented sphere was inserted into the packing line together with real fruits to record the magnitude and duration of each impact along the entire line.

The impacts experienced by the instrumented sphere while traveling along the packing line resulted in a total

acceleration of the fruit that was the vector sum of the three acceleration components on the X, Y, and Z axes. Total acceleration was studied using a variance component model. We hypothesized that different operations in fruit processing have different effects on the total acceleration and that these effects are not deterministic but can be treated as stochastic components.

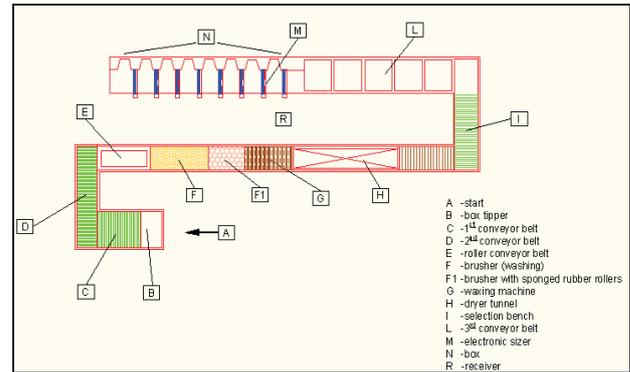


Fig. 3. Layout of the mandarin packing line and description of each step.

Among the considerations making this hypothesis plausible, we found that each step in fruit processing has unexplained characteristics related to observations over time. The different intercepts represent the level of acceleration that is typical of the processing step, and this has a certain effect on the level of total acceleration experienced by the fruit.

In this way, the acceleration of the fruit can be considered as the sum of a deterministic component (the average impact experienced by the fruit throughout the process) and a stochastic component linked to the various processing steps, which influence the impact experienced by the fruit. Formally, the impact estimation model is:

$$y_{ij} = \beta_0 + u_{0j} + \varepsilon_{ij} \quad (1)$$

where y_{ij} is the impact experienced by the fruit at the i th time ($i = 1, \dots, 3825$) during the j th stage of processing ($j = 1, \dots, 13$), coefficient β_0 represents the average impact experienced by the fruit throughout processing, and u_{0j} and ε_{ij} are random components that are stochastically independent ($u_{0j} \perp \varepsilon_{ij}$) with means equal to 0 and variances equal to $\sigma_{u_0}^2$ and σ^2 , respectively.

The Wald test was used to evaluate the existence of significant effects on the impacts recorded by the fruit in the various processing steps. In general, the null hypothesis that a certain regression parameter is 0, i.e.:

$$H_0: \hat{\gamma}_h = 0 \quad (2)$$

is tested with a Wald test:

$$W = \frac{\hat{\gamma}_h}{SE(\hat{\gamma}_h)} \quad (3)$$

where SE is standard error. This ratio has a standard normal distribution. The log-likelihood ratio test (LR test) was used for the random part of the model. When the parameters of a statistical model are estimated by the maximum likelihood method, the estimation provides the likelihood, which can be transformed into the deviance, defined as minus twice the natural logarithm of the likelihood. This deviance can be regarded as a measure of the lack of fit between the model and the data. In our case, we were interested in comparing the variance component model with a linear model. Let L_0 and L_1 be the log-likelihood values associated with the variance component and linear model, respectively. L_1 can be regarded as an extension of L_0 , with d_1-d_0 parameters added. The deviance difference test:

$$LR = -2(L_1 - L_0) \quad (4)$$

is approximately χ^2 distributed with d_1-d_0 degrees of freedom, where d_0 and d_1 are the degrees of freedom associated with the variance component and linear models, respectively. An intercapillar plot is a graphical tool used to determine if groups differ significantly. A level of significance of 5% was used.

III. RESULTS AND DISCUSSION

The accelerations imposed on the sensor node while the instrumented sphere traveled along the packing line were associated with the different steps in fruit processing (Table 1).

The waxing machine (step G) had the highest accelerations, reaching a maximum of 83 g.

Table 1. Total acceleration at different steps of packing line.

Step	Description	Duration (s)	Total acceleration (g)
A	Fruit arriving in box	9.5	3 to 25
B	Box tipper	0.5	1 to 4
C	First conveyor belt	4.0	1 to 4.5
D	Second conveyor belt	5.9	1 to 7
E	Roller conveyor belt	39.7	1 to 27
F	Brusher (washing)	61.6	1 to 73
F1	Brusher - sponge rollers	14.8	1 to 47
G	Waxing machine	35.4	1 to 83
H	Dryer tunnel	82.7	1 to 50
I	Selection bench	44.0	1 to 20
L	Third conveyor belt	14.5	1 to 8
M	Electronic sizer	10.2	1 to 19
N	Fruit falling into box	0.4	3 to 5

The statistical analysis showed no significant differences among the first five steps of the process (steps A to E), from fruit arrival to the roller conveyor belt. Step F (brusher) showed accelerations that differed from those recorded for steps C and D (conveyor belts). For step F1 (brusher with sponge rubber rollers), significant differences were found with steps C, D, E, and L, while the accelerations for step G (waxing) were significantly higher than all other steps, except steps A, F1, and N. In those three steps, the recorded accelerations were quite superimposable. Based on the impacts transmitted to the fruit, the most critical step was waxing (step G).

The results of the variance component model are shown in table 2. The fixed parameter (coefficient β_0) was highly significant and showed an average acceleration between 4.4 g and 6.1 g in 95% of the cases. The Wald test showed that the random components (u_{0j} and ε_{ij}) were significant in at least 5% of the cases, while the intraclass correlation, calculated from the ratio between the variance of the u_0 component and the overall variance, was 7.2%. This shows a non-zero correlation of the accelerations experienced by the fruit at each step of the process, which justifies the use of the variance component model.

Table 2. Results of variance component model for total acceleration.

	Coefficient	SE	p-Value	95% CI
β_0	5.22	0.43	0.00	4.38, 6.06
Random				
components	Estimate	SE	95% CI	Wald Test
$\sigma_{u_0}^2$	1.92	0.96	0.72, 5.13	2.00
σ^2	24.71	0.66	23.45, 26.04	37.44
Intraclass correlation	7.2%			

LR test versus linear model: $\chi_1^2 = 90.58$; $p \geq 0.00$

The LR test, which was used to compare the variance component model with a linear model, showed a high level of significance ($\chi_1^2 = 90.58$; $p > 0.00$), which also justified the use of the variance component model.

The intercapillar plot (Fig. 4) is useful to compare the significance of the average level of acceleration at the different steps. Non-overlapping ranges indicate steps that differ significantly at the 5% level.

Step F1 (brusher with sponge rubber rollers) and step G (waxing machine) showed the highest acceleration, while high variability was found in step N (falling into the box after sizing) and step B (box tipper). These steps had few observations and were therefore not interesting for the analysis.

No significant differences were found among the first five steps of the process (steps A to E), from fruit arrival to the roller conveyor belt. However, step F (brusher) showed accelerations that differed from those recorded for steps C and D (conveyor belts). For step F1 (brusher

with sponge rubber rollers), significant differences were found with steps C, D, E, and L, while the accelerations for step G (waxing) were significantly higher than all other steps, except steps A, F1, and N. In those three steps, the recorded accelerations were quite superimposable. Based on the impacts transmitted to the fruit, the most critical step was waxing (step G). The waxing machine therefore represents the step in which the greatest potential fruit damage can occur, thereby compromising the fruit quality.

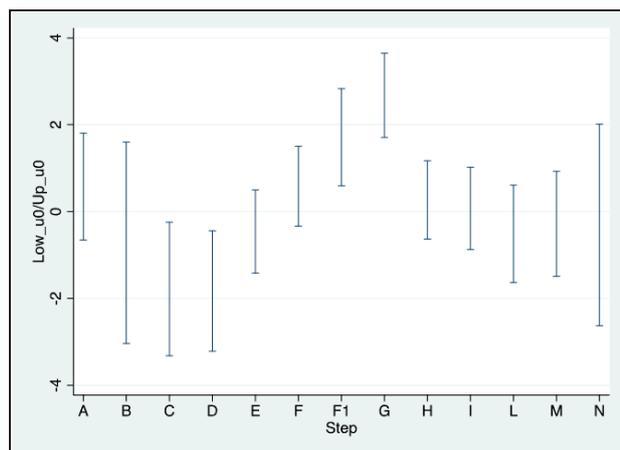


Fig. 4. Range plot comparing the significance ($p = 0.05$) of the average acceleration values for the packing line steps.

The variance component model for total acceleration indicated the significant differences between individual steps, and identified the waxing machine (step G) as the step in which the highest impacts occurred. Because bruising damage to fruit can be due to a single impact that is sufficiently energetic to create significant mechanical stress, the best approach is to analyze the individual steps of the packing line with a precise survey of the fruit passing through the packing line.

The waxing machine (step G) was identified as a point where the accelerations were significantly higher than in most of the other steps.

The prototype device allowed real-time visualization of the acceleration data for a fruit during processing and the magnitude of the impacts to which the fruit was subjected. This approach can improve packing line management [12] by allowing immediate intervention for adjustment of the process when damaging accelerations occur.

In [5], Fischer et al. identified the mean accelerations in a citrus packing line with a statistical comparison among what they called transference points based on ANOVA and Tukey's test; they measured most impacts within 30 g to 95 g and a maximum of 272 g at the point where the fruit entered the bin for degreening. The maximum acceleration recorded by Roa et al. [11] in a horizontal packing system (i.e., no height differences among the

machines) for oranges was $34.48 \text{ g} \pm 8.99 \text{ g}$, which is low compared to our study, while García-Ramos et al. [4] obtained the highest impacts (80 g) at the packing table entrance in oranges processing.

IV. CONCLUSIONS

A novel wireless instrumented sphere was implemented to evaluate the impacts experienced by 'Tardivo di Ciaculli' mandarins in a commercial citrus fruit packing line. The proposed instrumented sphere does not exist on the market; it was equipped with a wireless data transmission system and with a dedicated software and a GUI for real-time display of the recorded acceleration values.

Waxing was identified as the riskiest step because of the high accelerations (up to 80 g) recorded.

The presented instrumented sphere could be implemented with a real-time alert system capable of stopping the packing line if the recorded accelerations exceed a specified threshold, and the threshold could be different based on the products being processed.

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