Radiofrequency Sensing System for Fruit Quality Evaluation during Forced Ripening Processes

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Abstract

One of the most assessed methodologies in the food sector is the accelerated ripening of climacteric fruits within chambers with controlled environmental and gases conditions. However, nowadays, the management of the process is mainly based on qualitative estimations only, frequently resulting in poor fruits quality and scarce optimization of time and wastes. Following the modern paradigms of Industry 4.0, this contribution proposes a non-destructive RFID-based system for the automatic evaluation of the live ripening of avocados. The system, coupled with a properly trained automatic classification algorithm based on Support Vector Machines (SVMs), can discriminate the early stage of ripening with an accuracy greater than 85%.

1. Introduction

Ripening rooms are facilities used to artificially ripen fruits, vegetables, cheeses, and cured meats [1], by properly imposing, for a well-defined time, specific environmental conditions, such as temperature, relative humidity, ethylene, carbon dioxide and oxygen concentration.
The forced ripening is an assessed methodology specially for *climacteric fruits*, such as apples, bananas, and avocados. In this case, to control the process and hence ensure the proper status for the different destinations (which can be categorized as stock, grocery, or final consumer distribution), the firmness of the fruits must be carefully monitored. The monitoring is frequently done by qualified operators that manually evaluate the effectiveness of the forced ripening by visual inspection of the fruits, palpation, tasting [2], or the quantification of some parameters of the pulp [3]. These are usually destructive and qualitative tests and do not allow continuous monitoring. Furthermore, the recurring opening and closing of the ripening room alter the internal environment resulting in a waste of time, energy and, in general, of quality control [4].
For making the analysis more quantitative, non-destructive, and fully automatic, computer vision, potentiometric, and ultrasonic techniques have been proposed, as well as methods involving the sampling of chemical-physical parameters surrounding the fruits [5]-[7]. However, limitations to their spread acceptances are related to costs, easiness of the analysis and robustness of the response especially against the well-known fruit variability. The problem is hence still open.

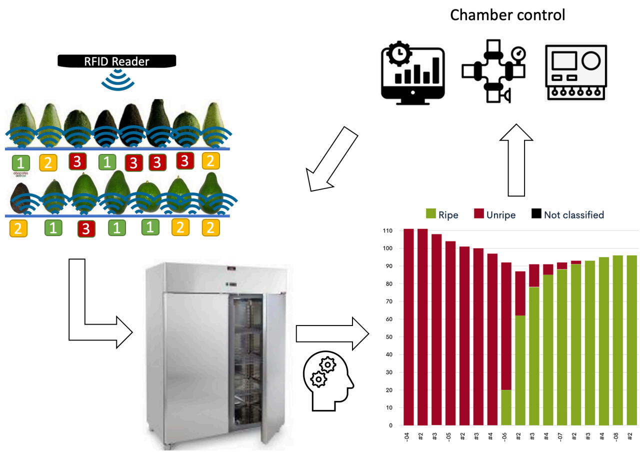

Figure 1. Scheme of the proposed monitoring system. Inside the ripening chamber, an RFID reader continuously interrogates passive tags in contact with fruits. By processing retrieved data through Artificial Intelligence algorithms, the ripening status is estimated, and the chamber state is consequently adapted in terms of exposure time, ethylene concentration, RH (relative humidity) and temperature.

Thanks to the current advances in Radio Frequency Identification-based automatic monitoring of objects [8] and even of people [9], the authors recently proposed the use of RFID technology for monitoring the ripening of avocado fruit packaged for final customer distribution in stores [10]. The system comprises intelligent packaging integrating a passive UHF RFID tag, a customized reader, and an elementary classification algorithm.

This paper instead introduces a passive, non-destructive UHF (860-960 MHz) RFID system for monitoring avocados state in industrial scenario. In agreement with the

modern Industry 4.0 trend, the system is aimed at supporting and finally at controlling the environmental conditions of the ripening rooms (time, temperature, relative humidity RH, concentrations of ethylene, carbon dioxide and oxygen) depending on the state of the monitored fruits (functioning scheme in Fig. 1).
The paper presents the design, the prototype and the test of the RF monitoring system, a trolley hosting 128 fruits and integrating an interrogation system with multiple reader antennas. Tags in contact with the fruits act as electromagnetic transducers: signals received and backscattered during communications are affected by changes when the fruit ripens [10], and thus they provide indirect information about the status of the fruit itself. Electromagnetic signals are then used to feed a classification algorithm based on Support Vector Machine (SVM), capable to discriminate the state of the fruits and classify it.

2. The Smart Trolley

The proposed monitoring system is a trolley (prototype in Fig.2) capable to host up to 128 avocados. Each fruit is placed in a properly designed plastic housing comprising 3 passive UHF tags. Tags are disposed to be in contact with the fruit in the equatorial and basal region. The four shelves integrate, in the basal portion, eight L11 Keonn near-field antennas each, for a total of 32 radiating elements. Antennas are connected to the M6 ThingMagic reader through four AdvanMux-8 multiplexers by Keonn. Reader is controlled by a proprietary SW framework running on a PC. The software oversees the measurement procedure, performs local processing of the retrieved data, applies machine learning techniques, (described in the following), and returns a visual indicator corresponding to the predicted ripening status of the fruit. All the electronic components are placed in a further fifth closed shelf, so that the trolley can be moved in the different ripening rooms of the packing house.

3. Rationale

If an antenna is placed in close proximity to the fruit (e.g., directly attached to the peel), any variation of the fruit properties will, in turn, produce modifications of the antenna's impedance and radiation gain, and definitively of the backscattered signals. By properly exploiting and mastering this phenomenon, a self-sensing, completely sensor-less, nondestructive, passive device is therefore obtained, wherein the sensor is the antenna, and the antenna is the sensor [11].

Let us denote with $\Psi(t)$ the ripening status of the fruit to be monitored by the RFID platform. The following electromagnetic indicators are returned by the reader and depend on the fruit condition $\Psi(t)$:

- $P_{R\to T}\,[\Psi(t)]$ - the transmitted power (dBm): the power delivered by the reader to the tag's chip;
- $P_{R\to T}^{to}\,[\Psi(t)]$ - the turn-on power (dBm): the minimum power entering the reader antenna to power up the tag;
- RSSI $[\Psi(t)]$ - the received signal strength indicator (dBm) related to the backscattered power $P_{R\leftarrow T}\,[\Psi(t)]$ from the tag to the reader;
- $\Phi[\Psi(t)]$ – The phase of the backscattered signals from the tag to the reader.

Starting from the above indicators, several metrics can be then derived by imposing different interrogation modalities (at fixed frequency, at fixed power or by scanning both as visible in Fig.3). The problem is, then, estimating the ripening process $\Psi(t)$ from the retrieved data.

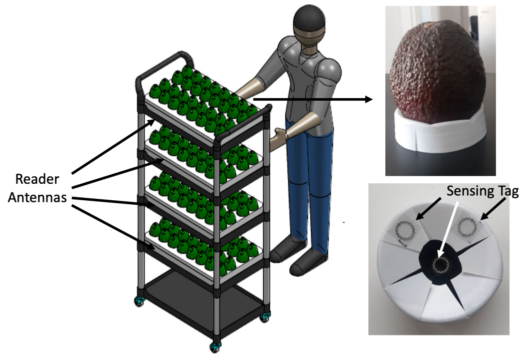

Figure ***2.*** Trolley for automatic monitoring of the ripening of avocados into ripening rooms. Four shelves host 128 fruits. Each fruit is in contact with 3 passive UHF tags integrated into the housing.

4. The classification algorithm

The prediction of the ripening stages relies on machine learning techniques applied to the electromagnetic data collected by the RFID system. Among several possible classifiers, the Support Vector Machine (SVM) is here applied. SVM is a supervised machine learning algorithm that can be used for both classification and regression [12]. SVMs are known as maximum margin classifiers as they find the best separating hyperplane between two classes. This process can also be applied recursively to allow the separation of any number of classes.
For the application to the ripening problem, the, classes have been defined according to the normalized Shore value (SH), i.e. the firmness hardness of each fruit as measured by the durometer, respect to the initial value at the beginning of the ripening process. During ripening, the fruits become softer, with an almost monotonic decreasing trend, as visible in Fig. 4. Three threshold values have been defined SH=□0.9, 0.8, 0.7□, corresponding to a ripening suitable for stock, grocery, or final consumer distribution, respectively.
The use of SVM involves a three-step procedure, namely the feature selections, the training and the testing phases.

For the training phase, a data set has been built by daily measuring each avocado. Each fruit was assigned to a ripening class according to the measured SH and the selected thresholds as in Fig.4. RF parameters were measured through the RFID trolley and processed to extract 30 features. Among them, a subset of 10 have been selected to feed the algorithm.

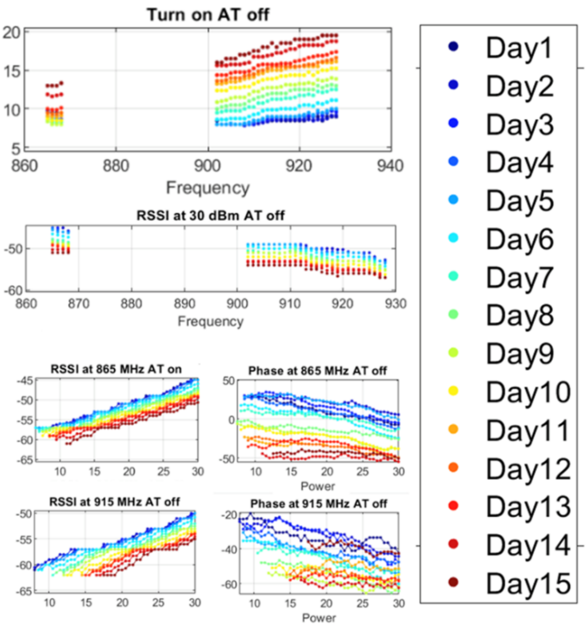

Figure 3. Example of different RF indicators retrieved from a single avocado when imposing different interrogation modalities.

4.1. Results

Fig.5 shows an example of classification of 128 avocados during a 10-days measurement campaign. Results are classified according to a *confusion matrix approach*: each day 4 possible cases can be obtained:

1. **True positive** (TP): The algorithm correctly evaluates the crossing of the threshold (Ripe)
2. **False positive** (FP): The algorithm wrongly evaluates the crossing of the threshold.
3. **False negative** (FN): The algorithm wrongly evaluates the not crossing of the threshold.
4. **True negative** (TN): The algorithm correctly evaluates the not crossing of the threshold (Unripe)

The first and the last conditions represent hence good evaluations.

Starting from the unripe state (TN-bars) fruits starts ripening with the progressive crossing of the threshold values. Along the days, the height of the TN-bars progressively decreases while the TP one increases. The excess of the threshold values is gradual: right after the first day of measurements some avocados reached the SH=0.9 value, while the third threshold SH=0.7 was met after 4-5 days.

Algorithm correctly classifies most of the events. Wrong evaluations mainly occur in proximity of the maturation, especially for the SH=0.9 level that implies an extremely early detection of the changes in avocados.
Overall, the average accuracy is greater than 85%.

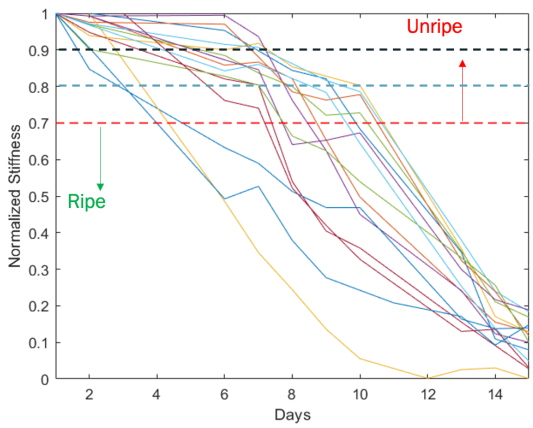

Figure 4: The SH versus ripening days for 16 avocados. Three thresholds indicate the ripening class and hence the hyperplane of the classification algorithm.

5. Conclusions

A system for automatically evaluating the ripening of avocados was proposed and tested. Each fruit is monitored by three sensor-tags. By analyzing RFID signals through SVM, an automatic classification of four ripening stages, can be achieved.
Early promising results gave prediction accuracies greater than 85%. Further improvements are expected by enriching the training dataset with a progressively higher number of measurements. Finally, additional UHF RFID chemical and physical sensors could be integrated into the same infrastructure as well to better sample and control the environmental condition in the close surrounding of the fruits.

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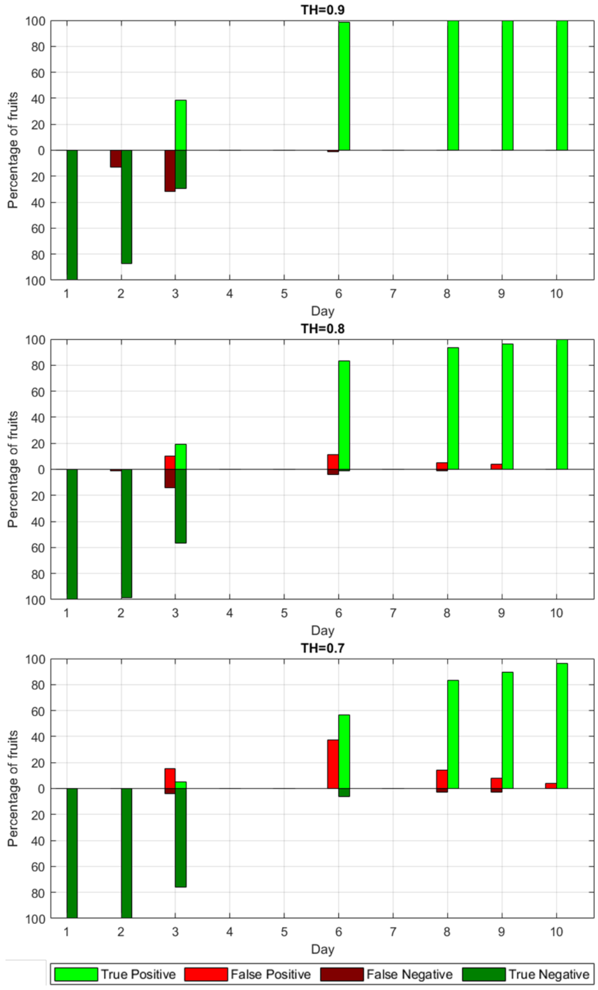

Figure 5. Results of 10-days monitoring of 128 fruits. The missing values refer to weekend days in which the manual measure of the SH was not possible, and hence no control on data correctness was available.

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