Organoleptic Properties Remote Sensing and Life-Time Prediction along the Perishables Goods Supply-Chain

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Abstract— Nowadays, two of the most compelling challenges in the field of food safety and certification are the reduction of the multitude of food losses and wastes in the supply chain and the improvement of certification and monitoring procedures during each stage of production. The aim of this paper is to propose an effective solution to both problems: a wireless sensor network (WSN) combined with a further data processing for real-time monitoring and shelf life prediction.

Keywords—Wireless Sensor Network; Safety; Food certification; Shelf life;

I. INTRODUCTION

One of the greatest challenges in the field of food production concerns food losses and wastes reduction. According to a study conducted by FAO [1], indeed, roughly one-third of food produced for human consumption, which amounts to about 1.3 billion tons per year, is lost or wasted globally. This alarming figure has clearly a double repercussion: on the one hand the food losses and wastes have a heavy impact on the economy of the industries, that, beside not being able to sustain the cost of the product through its sales, have to afford the high cost of disposal of these wastes; on the other hand, there are the negative effects of the high waste on the environment, resulting from the evident increase of waste and from the in vain use of production equipment. A further and no less important challenge in this field involves safety and certification. Global associations such as the FDA (“Food and drug administration”) or the WHO (“World Health Organization”) are continuously involved to promote more and more efficient monitoring and control methods [2]. This ongoing study aims not only to ensure a high standard of product quality, but also to protect the user from diseases due to consumption of injurious food. Nowadays, the most commonly used and diffused method to ensure food safety and certification in a supply-chain of perishables goods is the “Hazard analysis and critical control points” (HACCP). Essentially, the method suggests the identification of the different critical control points (CCPs) in the supply-chain and the definition of the parameters of interest for suitably monitoring every phase of the productive process. It is a scientific and systematic planning for the prevention of biological, chemical, and physical hazards whose seven fundamental principles are released and determined by the standard ISO 22000 [3]. Both the briefly explained problems, have a common node: the need of a versatile and efficient tool for improving food safety and certification through accurate monitoring during the entire supply chain, promoting, thus, a reduction in global food losses and waste. In this paper we propose a possible solution to these challenges: a wireless sensor network combined with a further data processing for real time shelf life prediction. The sections 2 and 3 propose the architecture of the WSN we built and used in a case study, a demonstrative monitoring of three storage conditions affecting the organoleptic properties of perishable goods, i.e. temperature, relative humidity and light exposition. The measurements have been realized in a warehouse for storage of agricultural products. Section 4 shows the possibility to predict the shelf life by the temperature monitoring. To this goal a calculation algorithm for the processing of the obtained data, based on a linear model of shelf life estimation governed by Arrhenius law is used. Section 5 shows an attempt of financial statement. Section 6 offers some final considerations, highlighting future developments.

II. Wireless Sensor Network

A. Definition and Generalities

A Wireless sensor network (WSN) is an infrastructure composed by wireless nodes, with little memory and a low-performance CPUs, capable of performing measurements, processing and communicating wirelessly to a central point, where the data are managed. The structure typically involves several wireless scattered nodes in a specific area periodically sending the collected data to a coordinator point (gateway), which manages the network and forwards them to another remote system for further processing [4]. The wireless access is usually a “contention-oriented random access” type, as defined in the IEEE 802, but IEEE 802.15.4 is the most commonly used standard (it defines the physical and MAC layers for Low PAN, wireless personal area networks with low data-rate) and ZigBee. This is due to IEEE 802.15.4 applicative advantages like worldwide defined operative band (2.4 GHz ISM), good data rate (250 kbps) and range of action, low power consumption, possibility of routing and retransmission in case of errors [5].
The OSI model can describe a WSN even if layer separation in a WSN is not so clear: the layers overlap each other in order to create efficient communication protocols, advanced power saving features and network flexibility. The second and third layer are the core of the network: they deal with solving the difficult challenges in a wireless sensor network just like scalability and communication problems. The physical layer plays a fundamental role, without whom the network would not even exist. The communication level, if implemented, is not defined by specific rules and, in any case, is not complicated as in the wired network TCP/IP. The levels 5, 6 and 7 are usually valid only for gateways or for hosts. ZigBee and other OEM solutions make exceptions networks, which also implement the application layer nodes [5], [6].

B. Architecture of a Light/ Temperature/ Relative Humidity WSN

The WSN built and used in our case study is made up of six nodes (fig. 1). Each node is equipped by a temperature sensor, ambient light sensor and relative humidity sensor. The node can process these data and send them to a coordinator (also called gateway) whose task is to make the received data available in real time (apart from the communication delays). The communication between each node and gateway is wireless using Zigbee protocol (2.4 GHz). The choice of this communication protocol is due to the need to have a long battery life that the Zigbee low power consumption can ensure. Later, the coordinator upload the data on a cloud using an HTTP connection. So data are available in real time and worldwide using any device with an internet connection just like tablets or smartphones by logging in the data cloud that manages the data. The appropriate authentication system allows access only to authorized users. Figure 2 shows a significant scheme of the overall architecture of a single node. The small size (6.85 cm x 6.35 cm x 3.30 cm) and independent power supply allow proper positioning of the sensors. As you can see, the analog output of each sensor is an input for the microcontroller.

It is equipped by a core, both RAM and Flash memory, real time counter, pulse width modulator, etc. Data are here converted into digital through a 12 bit resolution ADC [7]. After being processed, they are passed to the radio module in which they are modulated and sent using the Zigbee protocol at 2.4 GHz. The communication is guaranteed in a range of 40 meters indoor and 120 meters outdoor (line of sight). Table 1 summarizes the main characteristics of each node. It should be noticed that our WSN was just a demonstrator but it would not be difficult to improve the network using both more accurate and different sensors.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>6.85 cm x 6.35 cm x 3.30 cm</td>
</tr>
<tr>
<td>Weight</td>
<td>160</td>
</tr>
<tr>
<td>Power supply</td>
<td>1 per 30s/ 1.5y</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>+/- 2</td>
</tr>
<tr>
<td>Ambient light sensor</td>
<td>360 to 970 nm</td>
</tr>
<tr>
<td>Bandwidth Range</td>
<td>570 nm</td>
</tr>
<tr>
<td>Luminance range</td>
<td>10 to 1000 lux (+/-20%)</td>
</tr>
<tr>
<td>Relative humidity sensor</td>
<td>+/- 3% (0 to 59% RH)</td>
</tr>
<tr>
<td>Interchangeability</td>
<td>0 to 95% RH</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+/- 3.5% RH</td>
</tr>
<tr>
<td>Zigbee transmission</td>
<td>250kbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>2.4GHz</td>
</tr>
<tr>
<td>Indoor/line of sight range</td>
<td>40m / 120m</td>
</tr>
</tbody>
</table>

III. WSN MONITORING IN A PERISHABLES GOODS SUPPLY-CHAIN: EXPERIMENTAL RESULTS

To demonstrate the feasibility of the system and its functionality, we developed a case study. We performed at first a calibration of our WSN through a comparison with more accurate instruments in which the accuracy of the sensors is
outlined. Later we performed environmental monitoring of a warehouse in an industry producing dry and dehydrated food.

A. Working Verification through a Reference Given by Precision Instruments

Using more accurate reference instruments (lux meter: “Yokogawa 510 O2”; environmental hygrometer – thermometer: “Testo 608-H1”), we acquired 20 samples for each node (1 hour session - 1 sample per 3 minutes) and compared them with the reference instruments. The measurements were carried out indoor with artificial lights. Figure 3 shows the obtained graphs, where the red dashed line represents the reference. Table 2 presents data about average value, standard deviation and average error. The calculation of the standard deviation is useful in the evaluation of the precision: indeed, it returns the degree of convergence of our measurements. On the other hand it is also possible to evaluate the accuracy of the sensors, through an evaluation of “numerical distance” between the reference value and the measured value. Our measurements show that both accuracy and precision are sufficient for an environmental monitoring which therefore does not require extreme precision [8].

![Figure 3. Sensors accuracy verification (from the top relative humidity (RH %), luminance (lux) and temperature (°C)).](image)

Now we try to assess, although approximately, the total delay of the system. A first delay occurs in the communication node-gateway. Considering that each node sends three information of 32 bit each (96 bits in total) and that the Zigbee bit rate is 250kbps, we can estimate this delay to be about 0.000384 seconds (obtained from the ratio between the number of bits to send and bit rate). The communication delay between gateway and cloud is measured by the data service which showed, in our test, a maximum delay of 0.03 seconds. We can therefore approximate the communication delay between cloud-mobile/PC of the same order, as the data to be transferred and the type of connection are unchanged. The delay for algorithm calculation and for the alert sending from the mobile device depends on the characteristics of the device. However, considering a common reference processor that can handle 1 Gips, a period of 0.01 seconds is surely satisfactory. Therefore, the total delay of the entire system is estimated to be around 0.08 seconds. A certainly negligible delay for our application.

<table>
<thead>
<tr>
<th>Average absolute error (°C)</th>
<th>Average relative error (°C)</th>
<th>Standard Deviation [°C]</th>
<th>Average  relative error [%]</th>
<th>Standard Deviation [°C]</th>
<th>Average [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 0.04</td>
<td>19.78</td>
<td>3.89%</td>
<td>35.6</td>
<td>0.0060</td>
<td>5.46</td>
</tr>
<tr>
<td>S2 0.05</td>
<td>22.09</td>
<td>7.65%</td>
<td>19.05</td>
<td>0.0132</td>
<td>22.2</td>
</tr>
<tr>
<td>S3 0.04</td>
<td>24.08</td>
<td>21.82%</td>
<td>19.05</td>
<td>0.0060</td>
<td>24.1</td>
</tr>
<tr>
<td>S4 0.04</td>
<td>26.07</td>
<td>3.89%</td>
<td>35.6</td>
<td>0.0060</td>
<td>26.1</td>
</tr>
<tr>
<td>S5 0.04</td>
<td>28.06</td>
<td>8.06%</td>
<td>19.05</td>
<td>0.0132</td>
<td>28.2</td>
</tr>
<tr>
<td>S6 0.04</td>
<td>30.05</td>
<td>13.90%</td>
<td>35.6</td>
<td>0.0060</td>
<td>30.2</td>
</tr>
<tr>
<td>Ref.</td>
<td>22.21</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

B. 24-Hours Demonstrative Warehouse Monitoring Using a Real Time Light / Temperature/ Relative Humidity WSN

According to the purpose of demonstrating the potentiality and the feasibility of the system, we performed a 24-hour monitoring demonstration in the warehouse of a manufacturer of dehydrated and dried foods. The duration of our monitoring was 24 hours, but this could have been much longer without any problems: monitoring of months or even a year would have been equally possible considering the life of the batteries. On the contrary, the objective is to ensure a long-term monitoring. As figure 4 shows, we placed 3 nodes: one monitoring a pallet outdoor (in green), one monitoring a pallet indoor (in orange) and the last one
monitoring a box indoor (in yellow). The session was a 24-hours acquisition, in which we have stored one sample - for temperature, light and relative humidity - every 3 seconds and then we averaged these values in time windows of 30 minutes (average of 10 samples). The data collected and stored were available to any authorized user in the world in real time (apart from communication delays). Thanks to the battery life durability, it would be possible a monitoring of the entire food chain in the same way. This would promote transparency in the food chain, becoming a guarantee for the consumer, a powerful low-cost tool for the producer and a simple control method for the organs predisposed.

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IV. SHELF LIFE AND QUALITY DEGRADATION RATE ESTIMATION

Shelf life is the period of time in which a perishable product may be stored without changing its organoleptic properties. Strictly connected to the shelf life is the quality degradation speed. It depends on a multitude of variables that can be split in internal (like packaging, composition etc...) and environmental ones. Several approaches have been developed to estimate shelf life; in our study, as example, we propose to analyze the temperature data through the Arrhenius law to estimate the shelf life and the degradation rate of the agricultural products monitored using the WSN whose characteristics are defined in a standard situation. In reality the combination of the law regulating the full set of the parameters under measure could give a more realistic shelf life estimation. Nevertheless in order to explain the procedure we describe the algorithm in use considering the temperature as the main parameter affecting the shelf life.

A. Linear Mathematical Model of Quality Degradation Prediction

Among the several variables which determine the rate of degradation, one of the heaviest is certainly the temperature. In our approximate mathematical model, we consider the internal variables of the product fixed and the environmental conditions (mainly temperature) affected by variations [11]. The relationship between product quality (denoted by C in this treatment) and its life-time can be reasonable approximated as linear and inversely proportional. The gradient of the line (K) represents the quality degradation speed and depends on the temperature according to Arrhenius law [9], [10], [11]:

\[
\frac{dc}{dt} = K(T) = W e^{-\frac{E_a}{RT}}. \quad (1)
\]

It is rational to consider a reference condition available given by legislation or manufacturer's instructions (blue line in fig. 5). In particular, the following quantities have to be considered known:

- \(C_0\): Best quality condition (100% in a normalized treatment);
- \(C_e\): Lower quality limit (expressible in percentage, too);
- \(t_s\): Reference shelf life;
- \(T_0\): Recommended temperature.

![Figure 4. Five hours pallet monitoring results (from the top, temperature (°C), relative humidity (Rh %) and luminance (lux)).](image)

The calculation of the quality degradation speed in a reference scenario is immediate:

\[
K_0 = \frac{C_e - C_0}{t_s}. \quad (2)
\]

Let us assume that, due to an environmental perturbation, at time \(t_1\) the temperature rises to a value \(T_1 > T_0\). The shelf life, then, must decrease (\(ts1 < ts0\)) accordingly to the new quality

![Figure 5. Linear model of quality degradation.](image)
degradation rate ($K_1$) that can be estimated using the Arrhenius law (1). The new behavior of the quality versus time can be expressed as (green line in fig.5) [16], [17]:

$$C = k_1 \cdot t + \frac{c_1}{K_1 \cdot t_1}$$  \hspace{1cm} (3)

If the new conditions are too stressful for the product, even if the temperature returns to $T_0$ later, the shelf life must not change (red line in fig.5): by now the product is compromised, applying the prevention principle.

B. Presentation of a Calculation Algorithm for the Shelf Life Estimation

The mathematical model described can be implemented in a calculation algorithm (fig. 6). This can be used to create an application for smartphones or tablet in order to set a friendly and intuitive interface with the WSN data. The algorithm gives a real time prevision of the left shelf life of the monitored product allowing an immediate preventive intervention. For the calculation process a database in which all the required constant values are stored is necessary. The main steps of the process are described below.

i. Get reference values: $SL_0$ (inserted in hours), temperature ($T_0$), Humidity ($H_0$) and luminance ($Lx_0$).

ii. Acquire real time $T$, $H$, $Lx$ from the WSN and show them.

iii. Define appropriate variables

iv. Compare real time values with the references: If current condition is similar to the reference (in a settable range) calculate $K_0$: the $SL$ is the same as the $SL_0$ (of reference).

v. If strong environmental changes have occurred, give an alert signal.

- Through Arrhenius law (1), calculate the new degradation speed coefficient ($K$).
- Predict the new shelf life as a fraction of the standard one: the new shelf time is calculated using the ratio between $K_0$ and $K$.
- The new $SL$ has to be considered as a maximum limit: now the product has been compromised (in a preventive view) and the $SL$ cannot increase any longer (even if better conditions occur).

vi. Show remaining shelf life and repeat the loop every hour (settable option).

When the system returns the value 0 as the shelf life, the product no longer meets quality standards and is considered expired.

C. Shelf Life Accuracy

The calculation system proposed presents a certain degree of approximation. Firstly, the calculation is made assuming the degradation as a linear function of time although in reality it is not. Moreover, considering that the temperature sensor used has an accuracy of $\pm 0.2^\circ C$ we can reasonably assume that the new value of the rate of degradation $K_1$ is to be understood between a $K_1-$ and a $K_1+$ evaluated according to the Arrhenius law (1), respectively, at $T_1-2^\circ C$ and to $T_1+2^\circ C$. Therefore the shelf time is valid in an interval between $ts_-$ and $ts_+$, obtained from eq. (3), using respectively $K_1-$ and $K_1+$. However, the accuracy of the system can surely be improved by using more accurate sensors for the evaluation of the temperature and implementing
V. FINANCIAL CONSIDERATIONS: COSTS AND BENEFITS

The solution is not expensive and allows a safe monitoring of several typology of goods. Just for give an estimation of the costs let’s try to make a budget statement. If produced in a supply chain, we can estimate the cost of each node of about €15 (considering nodes of high quality with re-programmability and reusability characteristics) and about €500 for each gateway. A system made by 3 gateways and 45 sensors (considered sufficient to manage a medium-sized productive environment) would cost about € 2,175. Estimating the lifetime of the gateway (changing individual nodes is not a problem) for about 4 years, we are talking about € 544 annually. Regarding the shelf life estimation and the implementation of the dedicated application, we can assume - in a supply chain - which cost is negligible compared to the WSN one. These costs would certainly be overcome by the consequence reduction of wastage in perishables chain and the lack of relative costs of disposal and the corresponding increase in sales (due to the added value that such a monitoring system can provide the product).

Technological feasibility and lack of the costs make the system an effective tool in a supply chain of perishable goods.

VI. CONCLUSIONS

In this paper a case study for a WSN architecture and a demonstrative monitoring of three storage conditions affecting the organoleptic properties of perishable goods, i.e. temperature, humidity and light exposition has been described. The measurements have been realized in a warehouse for storage of agricultural products. The algorithm for the processing of the obtained data and giving the shelf life estimation through the Arrhenius law is also discussed.

As concern the hardware, it would not be difficult to implement a GPS system and a GSM communication on each node in order to overcome the limitation of the presence of the gateway and provide useful information for traceability. The data processing can be improved through the implementation of a pathogens database: the proliferation of these agents occurs under specific conditions of temperature, humidity and light. It would not be difficult for the system, to predict whether the product is or will be submitted to environmental conditions favor of to the development of some pathogen. Furthermore, through appropriate actuators, it would be possible to allow not only the monitoring but the control of the production environment, making human intervention superfluous. The method here proposed is advantageous and suitable for a low cost implementation and allows at the same time a reduction of the wastes in the supply chain by a right evaluation of the product life and an improvement of food safety and certification.

ACKNOWLEDGEMENT

The presented work has been carried out in the frame of the "RIDITT CESAR" project (PON R&C 2007 -2013 – MISE D.M. 22 July 2009 – “Food safety and certification using RFID technology”) promoted by the Italian Ministry of Economic Development, whose aim is to improve food safety and certification.

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