Combination of WSN and 1st Order Kinetic Model for Real-Time Shelf-Life Prediction of Perishable Goods

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I. INTRODUCTION
Combining the environmental monitoring by a Wireless Sensor Network (WSN) with a further real-time data processing of collected data, is possible not only to detect not recommended manufacturing, storage and distribution conditions but also to evaluate how an incorrect environment spoils product quality in order to both improving food safety and certification and reducing Food Losses and Wastes (FLW). A typical parameter employed for evaluating product freshness during the storage or distribution phases is shelf-life, that is the period of time when a perishable product still exhibits sensory, chemical, physical and microbiological characteristics compliant with the human use.

II. WIRELESS SENSOR NETWORK ARCHITECTURE
The WSN employed in the present study consists of multi-sensing nodes, equipped with temperature (±2°K accuracy), relative humidity (8%rh accuracy) and light exposition sensors. The internal microcontroller represents the core of each node: it includes a 12-bit resolution ADC, employed for sensor data digitalization, and an RF module, which supports ZigBEE protocol (IEEE-802.15.4). Each node has a small size (6.85cm x 6.35cm x 3.30cm) and is powered with 3x1.5V AA batteries. The choice of ZigBEE protocol resulted from the tradeoff between power consumption (<1mW), data rate and transmission rate (250 kbps). The network coordinator uploads the collected data on a cloud service using an internet connection (LAN or GPRS).

III. SHELF LIFE PREDICTION ALGORITHM
The decay of perishable goods results from several physical, chemical and microbiological reactions, which depend on variables such as temperature, humidity and light exposition and many more. Although quality decay behavior differs from a product to another one, a general 1st order model that effectively approximates its behavior is given by:

\[ c = c_0 e^{-kt} \]

where \( k(T) = W e^{-E_a/RT} \) (Arrhenius Law)

where \( c \) is the quality level of the product, \( c_0 \) its initial condition \( k \) is the reaction rate constant. Since temperature is the most significant parameter in chemical reactions, the rate constant \( k \) can be related to absolute temperature \( T \) according to Arrhenius law, in which \( W \) is the pre-exponential factor, \( E_a \) the activation energy and \( R \) the gas constant. If the constants of the process are known, the new shelf-time (SL') due to a temperature variation can be calculated as:

\[ SL' = \frac{1}{k(T)} \ln \left( \frac{c'}{c_{\text{min}}} \right) \]

After having defined the theoretical model, a monitoring algorithm for the real-time shelf-life prediction has been developed. The main steps of the algorithm are here summarized below:

1) Get reference values of temperature, humidity, luminance and the parameters of the kinetic model of the considered reaction (for each monitored product).
2) Determine the reference value of the rate constant \( k \) and the starting value of shelf-life.
3) Start the monitoring loop (one hour per iteration): Acquire current values of environmental variables.
4) Compare current parameters with the reference ones.
5) If recommended conditions are met, use \( k_{\text{ref}} \) value for the calculation of the new concentration and shelf-life;
6) Otherwise send an alarm and calculate:
   i. the new rate constant \( k(T) \); ii. the new quality level;
   iii. the new shelf-life value;
7) Plot remaining shelf-life and repeat the loop.

IV. A CASE STUDY: 8 DAYS WAREHOUSE MONITORING
Here we report the highlight of a 8-days monitoring in a warehouse of vegetables (fresh tomato mainly). The WSN used was made up 6 multi-sensing nodes. Figure 1 shows the experimental results and the shelf-life prediction after the 8-days experience. As predicted, nodes 3 and 4 exhibit an eight days shelf-life (they are monitoring vegetables at recommended temperature), whereas node 1 and 2 showed a longer one (almost twice) due to the lower temperatures. On the contrary, node 5 and 6 ended faster their shelf-life since the storage temperature was about 10 °C higher than the recommended one.

V. CONCLUSIONS AND FUTURE PERSPECTIVES
The proposed multi-sensing platform is a complete and autonomous system, easy to be implemented and able to calculate in real time the quality degradation of the product, a parameter, this, difficult to assess. Further studies contemplate the development of a more accurate model, including – for example – light and humidity exposition, in order to predict and classify the bacteria development under unsafety conservation condition.

Figure 1: Temperature History (left) and Shelf-Life computation (right) at the end of 8-days monitoring.