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Shelf life prediction by intelligent RFID Technical limits of model accuracy

Reiner Jedermann[1], Jean-Pierre Emond[2] and Walter Lang[1]

[1] Institute for Microsensors, -actuators and –systems, {rjedermann|wlang}@imsas.uni-bremen.de
[2] UF/IFAS Center for Food Distribution and Retailing, jpemond@gmail.com

Summary. *Information about current quality state enables large improvements in the dynamic planning for the logistics of fresh products. The main reason for quality losses are temperature deviations. This article investigates how a prediction system that delivers a shelf life prediction at each transhipment point could be integrated into a semi-passive RFID label. Limiting factors for the possible predictions accuracy like model tolerances and the bound processing resources of low-power microcontrollers will be evaluated.*

Keywords: Semi passive RFID, shelf life models, temperature supervision

Introduction

Fresh perishables are a great challenge for retailers. These products must move as fast as possible in order to provide the best quality to the consumers. For some produce only few hours delayed in cooling or in the distribution chain can be sufficient to prevent their marketability. Today, new knowledge and technologies can allow better control of the distribution chain from field/processing to store.

For many retailers the best way to keep or gain market share is by presenting an attractive produce section. A positive image of the produce department gives the customers a better perception of the quality of the business. In the minds of many customers, if the store provides a high quality fresh produce, it probably maintains the same high quality for the other products in the store. The visible attributes of the produce, that is the appearance of the produce is maybe the most important factor that determines the market value of fresh fruit and vegetables. However, the price to pay to keep the “image of freshness” is to have an inventory turnover of almost 50% per day. This is the highest percentage in a retail store followed by the meat and fish sections. One of the reasons is the perishable aspect of the produce. Most of the time, conditions found in the store are far from the recommended temperature and humidity needed to maintaining an optimal produce quality. Often, a short exposure of 1 or 2 hours to inadequate conditions (i.e. too high or too low temperatures, too dry or too moist) is enough to cause a dramatically drop in the visual quality of a produce.

Nunes et al. [1] reported that temperature is the characteristic of the distribution environment that has the greatest impact on the storage life and safety of fresh perishables. Effective temperature management is in fact, the most important and simplest procedure for delaying product deterioration [1]. For example, optimum temperature storage retards aging of fruit and vegetables, softening, textural and colour changes, as well as slowing undesirable metabolic changes, moisture loss, and loss due to pathogen invasion. Temperature is also the factor that can be easily and promptly controlled. Preservation of perishables quality and safety can be only achieved when the product is maintained under its optimum temperature as soon as possible after harvest or production.

Understanding more about the whole distribution chain is important. Knowing in advance what it is going to happen is critical. Any systems that can communicate additional information regarding shipment quality and safety aspects before it gets to the distribution centre are essential from a quality assurance perspective. Currently, most digital temperature loggers have to somehow be connected to a host device to download data, and because of this, they have limited ‘real-time’ data interactivity, and result in after-the-fact analysis for claims, quality analysis and related issues. RFID temperature loggers add wireless communication to read the temperature logger in real-time. The RFID tag, with associated hardware and software will add the benefit of having a pallet/tag scanned on receipt, so that if an alert (alert trigger programmable prior to shipping) is active, the receiver knows immediately (not after-the-fact) that there is a potential problem with the shipment and can spend the time required on specific shipments rather to use random inspections.

This new approach can enable retailers and suppliers to plan the movement of perishable products more efficiently and thus reducing waste and providing better quality products to consumers. A study done by Pelletier et al. [2] demonstrated that knowing the full temperature history from the field to the distribution centre can make a difference of as much as $48000 of loss of revenue per trailer of strawberries for a retailer. Further study done by Emond et al. [3] demonstrated that for fresh strawberries the full visibility of the temperature of the shipment combined with a shelf life prediction model can bring $13,076 in profit per trailer compared to a potential lost of $2,303 with the actual process.

This full visibility combined with prediction models can allow retailers, food service and restaurant chains to manage their inventories by First to *expire* – first out (FEFO) rather than first in - first out (FIFO). Prediction shelf life models like the ones developed by Nunes et al. [4] can integrate the quality attributes selected by the users and predict which loads should be sent to specific stores or restaurants in order to maximize inventories and quality.

Intelligent RFID as enabling technology

One technical challenge for the implementation of the described quality and temperature tracking system is the management of the huge data amount. Especially the communication between reader and passive RFID device turned out to be a major bottleneck. Reading full temperature charts from hundreds of RFID data loggers at each transhipment point is hardly possible. On the other hand, for quality based inventory and transport management it is rather sufficient to have an indicator for current quality and pending losses than knowing the detailed temperature history.

The approach of the 'intelligent RFID' circumvents the communications bottleneck and provides the necessary information for management by integration of the shelf life model into the hardware of an RFID temperature logger. After being configured by the producer (Step1), the intelligent RFID measures the temperature during transport and calculated the change in the product properties per time unit (Step 2). When passing a reader gate at transhipment the RFID tag only transmits the calculated quality state of the attached transport good (Step 3). A traffic light signals whether the product is 'ok' (green) or needs additional checking ('red'). The temperature history of products in a crucial state can be read out by a handheld reader (Step 4) for detailed analyses [5]. The process of transport supervision by intelligent RFID is depicted in **Fig. 1**. An alternate approach that allows online access to temperature and quality during transport on the costs of higher hardware expenses, the intelligent container (www.intelligentcontainer.com) is described in [6].

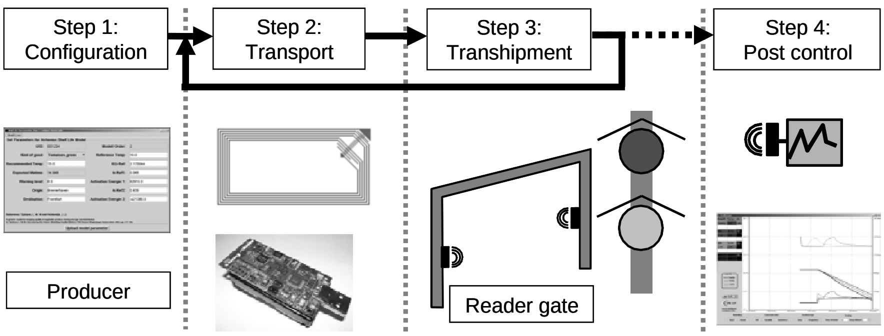

Fig. 1. Transport supervision by intelligent RFID

Modelling approaches

Beside the technological basis, the precise modelling of shelf-life changes is the other key challenge. One very common approach is to describe the quality decay according to the law of Arrhenius for reaction kinetics. The change in shelf life or loss per day is calculated as a function of temperature [6].

These shelf life or keeping quality models have the advantage that only three model parameters have to be estimated by analysing experimental data. Tijskens [7] showed that the sensitivity of some fruits against chilling injuries caused by too low temperatures can be modelled by adding a second Arrhenius type function with negative activation energy, resulting in five parameters in total.

For many food products, a chain of chemical or enzymatic processes contribute to a loss of quality. The approximation by one or two Arrhenius function does not always deliver the required accuracy. For a precise prediction the time function of several quality factors like colour, firmness, mould and vitamin C content, have to be estimated. Because it is not possible to know in advance which of the curves will be the most critical one, all of them have to be continuously calculated and monitored.

Descriptions of the underlying chemical reactions by a set of differential equations are only known for a minority of products, Bobelyn [8] for example describes the colour loss of Mushrooms by a set of 3 or 6 equations.

In many cases only tables for different constant temperatures are available, listing the change of physical properties over time. Examples can be found in [9] and [4]. To extract a set of differential equations from these measurements requires expert chemical knowledge that is in general not available.

The suggested table-shift approach provides a prediction for dynamic temperature condition based on curves recorded at constant temperatures. The value of each physical property for the next step is read out from the pre-measured table. If the temperature changes, the focus in the table is shifted to the row that matches the current quality inside the column for the new temperature. In the mathematical description the change per physical property is calculated as two-dimensional interpolation over the parameters temperature and current property state.

Software simulation for the table-shift approach

This table-shift approach was verified by a MATLAB software simulation. The prediction might be distorted by effects of unknown or hidden states that also affect the speed of change. Full accuracy can only be guaranteed, if all underlying reactions have the same relation to temperature or activation energy. In this case a change of temperature can be expressed as a stretch of the time scale.

If the activation energies are close to each other, the table-shift approach will give a good approximation. As example the table-shift model was compared with a 3 differential equation sigmoid model for the browning of mushrooms described by Bobelyn [8]. The reactions that contribute to the oxidation of the colour pigment have activation energies of 74600 and 65500 J mol^{-1}. In the first step a table for colour change over time was created for four different temperatures by simulation of the differential equations. **Fig. 2** shows the colour change for an arbitrary temperature function calculated by the differential equations and by interpolation of the tables. The effect of the differences in the activation energy turned out to be minimal.

A more crucial problem are tolerances of the measured table values. Measurements of physical properties like firmness or nutrition content have only a very limited resolution. Taste and aroma are evaluated on a subjective scale. The effects of a measurement resolution limited to 1% or 5% of the maximum value were also tested by the MATLAB simulation in Fig. 2.

To avoid misleading results, the accuracy of the table-shift model has to be verified for each product by simulation for a dynamic temperature curve. Possible deviations caused by different harvest conditions should also be tested.

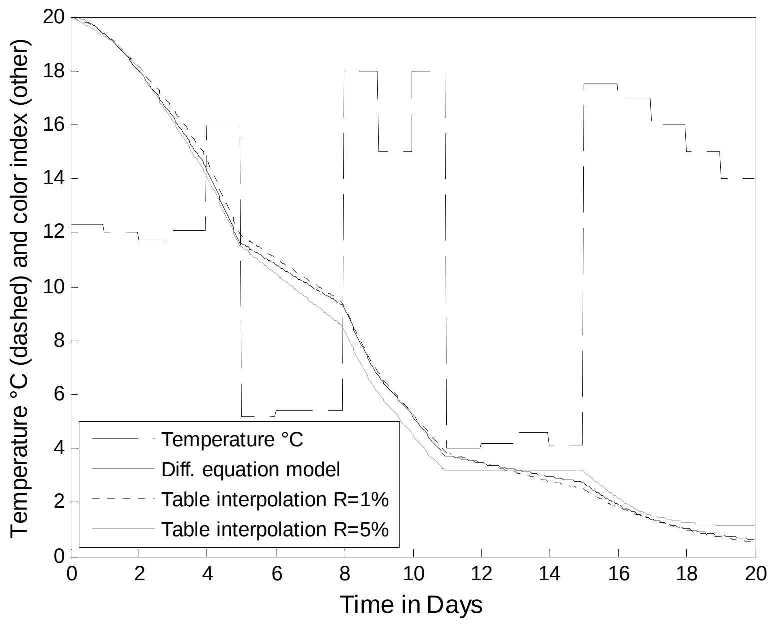

Fig. 2. Matlab simulation of predicted colour loss by differential equation model and table shift model with table resolution of 1% and 5% for an arbitrary temperature input. Colour index scaled to 20 as initial value.

Implementation

Several developments can be found that point into the direction of a low-cost shelf life tag. The Turbo-Tag data logger from Sealed Air / KSW Microtec (www.turbo-tag.com) uses a semi-passive RFID tag equipped with an additional battery to record up to 700 temperature values. A number of manufactures announced UHF RFID temperature recorders with extended reading range.

Some data loggers already include shelf life estimation, but are restricted to Arrhenius type models. The electronic time temperature integrator from CliniSense [10] can be ordered in small quantities, but it does not offer RF communication. The announced Freshtime tag from Infratab is still not available yet.

Wireless sensor networks (WSN) provide the second platform for a shelf life monitoring device beside passive RFID. Ranges of 50 meters or more are reached by active communication. The Tmote Sky from Moteiv (www.moteiv.com) is equipped with a free programmable MSP430 ultra-low-power microcontroller running at 8 MHz clock rate with 16 bit integer arithmetic and hardware multiplier. Drawbacks are the higher price, energy consumption and resulting battery size.

Because currently only WSN offer additional on-board calculation facilities, first tests of different model types were carried out on this platform. Our demonstration system measures the freight temperature and sends a calculated quality index over a 2.4 GHz link to a PC. Three different model types can be uploaded to the sensor notes: The first model calculated losses directly by two Arrhenius functions. The second micro controller application is based on a pre-calculated look up table for the loss per day as function of temperature as proposed in [11]. The tables were generated by evaluation of the same equations that were used in the first model. The table-shift approach with two-dimensional interpolation was tested as third application.

Required resources

To transfer the model calculation to a semi-passive RFID tag, a new hardware development will be necessary. As preliminary step for construction of an intelligent RFID it should be carefully considered, which model types and level of accuracy are feasible inside a credit card sized label in regard to limited processing power and energy resources.

Quality modelling can be seen as add-on to existing data logger technology, which provides required system components as RFID interface, sensor query, accurate timer and data storage, powered by a paper thin battery. So the question is to determine the additional costs for quality modelling.

To answer this question the required resources for the implementation on the wireless sensor platform were analysed. The required energy per model step was calculated based on the measured execution time of the modelling algorithm. The necessary memory resources for the program in ROM as well as variables and constant tables in RAM were extracted from the compiler log file. The results for the both considered models are summarized in **Table 1**.

Table 1. Required resources per model step

Type of Resource	Calculation of Arrhenius equations	Look up table for Arrhenius model	Table-Shift Approach
Processing time	1.02 ms	0.14 ms	1.2 ms
Program memory	868 bytes	408 bytes	1098 bytes
RAM memory	58 bytes	122 bytes	428 bytes
Energy	6 µJoule	0.8 µJoule	7 µJoule

The required energy has to be compared against the battery capacity and the stand-by current of the microcontroller.

The table-shift model consumes about 10 times more energy than the interpolation of a one-dimensional look up table. But the consumption of the table-shift model is still negligible compared to the capacity of small size batteries. If the shelf life of quality state is updated every 15 minutes, 20 mJ are required per modelled physical property and month. A typical button cell battery has a capacity between 300 J and 3000 J. The Zink oxide battery of the credit card sized turbo tag data loggers has a capacity of 80 J.

Design issues for the RFID implementation

A more crucial issue is the stand-by current of the microcontroller. Although the microcontroller does nothing 99.99% of the time, it still consumes energy for the clock oscillator, wake-up circuit and RAM retention. The typical stand-by current of the MSP430 of 1 µA at 2.2 V results in a consumption of 5.7 J per month.

From the point of required resources precise quality prediction including modelling the temperature dependency of several physical properties will be feasible. The challenge is rather to add integer arithmetic capabilities to a semi-passive RFID tag without increasing the stand-by current to much.

Summary and outlook

Losses of perishable good can be avoided by managing transport and warehouse planning based on the current quality state. To install this process two elements are necessary: Accurate shelf life models and a way for efficiently measure the freight conditions and deliver this information.

In most cases it is hard to develop a bio-chemical model to describe the change of physical product properties as a function of temperature and time. The table-shift approach provides a method for a direct calculation of the shelf life based on a set of measured reference curves. The accuracy of this approach has to be validated for new product types by comparison of simulated curves for dynamic temperature conditions with measured data.

Intelligent RFID is the most promising concept to capture temperature and forward quality information without trapping into communication bottlenecks. This approach will probably not provide multi-factor quality parameters details like as a main frame system but still can provide rapid information for immediate response at any steps of the distribution chain. Although no hardware solution is currently available, the measurements of the required resources demonstrate that it would be possible to integrate the calculation of a shelf life model into an RFID temperature logger. Limiting factors for the model accuracy are measurement tolerances of the pre-recorded reference curves. Related experiments to connect a low-power microcontroller with an UHF-RFID communication interface are currently carried out by the IMSAS.

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