Linking keeping quality models and sensor systems to an autonomous transport supervision system

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Abstract: *The development of concise supervision systems to monitor quality changes during transport of fresh fruits and of other perishable foods demands cooperation between agricultural and micro electronic research. Special sensors are required to measure parameters that influence product quality. Beside temperature and time, ethylene has an important effect on the keeping quality. We discuss micromechanical sensor concepts for application in reefers or trucks. The assessment of the effect of temperature, time and sensor data needs models to assess the keeping quality, the time a product remains acceptable for consumers. Using tomato as example we show how different harvest conditions influence the keeping quality. Our reduced scale prototype demonstrates that it is feasible to integrate a real-time supervision system into standard reefer trucks or containers. The keeping quality is calculated on a credit card sized processor module. Information to select the appropriate model type is stored on a standard RFID tag that is attached to the freight item.*

1 Introduction

Transport planning for fresh fruits and vegetables has to deal with the risk that the quality of a consignment falls below an acceptance limit. This would not only mean loss of the freight but also cause conflicts with delivery commitments. Providing information the moment it becomes available reduces these risks considerably.

Concise supervision and modelling of product behaviour that includes the effect of time and temperature enables prediction of the keeping quality, the time a product remains acceptable [Scho98]. These models could be either used for offline simulation of transport conditions to detect critical parts of the supply chain or to improve the transport and warehouse planning by online data. Warehouse management in distribution centres would be much more efficient if it is organised based on keeping quality estimations instead of the principle of 'first-in first-out' (FIFO).

New developments in logistics use two major technologies to improve the supervision of the cold chain: Mobile networks for telemetric monitoring of (reefer-) containers and integrated time temperature quality modelling to monitor quality changes during transport to predict the keeping quality at unpacking.

By cooperation between agricultural science and micro electronic research we are developing an autonomous transport monitoring system based on these technologies. An embedded processor module calculates on the basis of a keeping quality model and sensor data, the time left before a product becomes unacceptable for consumers. Local data handling reduces costs for mobile communication, but allows permanent access to the quality and sensor state. By using mathematical modelling, instead of e.g. chemical reactions (TTI's), the system can adapt easily to new products. Information to select the correct model is stored on a standard RFID tag.

The first application tested on our laboratory scale prototype will predict the keeping quality of tomatoes based on time-temperature measurements in real time. In practice, variations in harvest maturity and concentration of the ripening inducer ethylene will influence the keeping quality significantly.

The transfer of our prototype to a ready to market system has to face various challenges. Beside improvements of the technical system and research in sensor technology, kinetic models and methods to measure harvest maturity have to be developed.

1.1 Factors influencing keeping quality

The main factors influencing quality behaviour during postharvest transport are generally temperature and time. A lower temperature and a shorter transport time are generally advantageous in terms of keeping quality. However, some products are very sensitive to low temperature decay (also called chilling injury that occurs typically for products that originate from the (sub) tropics). Also, unripe products will not ripen when stored at low temperatures, but might ripen when stored at an alleviated temperature due to the production of ethylene.

Fruits (and vegetables) can be divided into two groups: climacteric and non-climacteric. Ripening of non-climacteric fruit is generally considered to be ethylene-independent. In climacteric fruit, ethylene can inhibit or stimulate its own production, depending on the physiological phase of the fruit. The first phase shows auto-inhibition of ethylene production (pre-climacteric stage, immature). This is followed by a phase with autocatalytic ethylene production (climacteric stage, ripening). Both temperature and time will have a large impact on the ethylene production and therefore on product behaviour due to ethylene inducing and stimulating ripening (synthesis of colour components, loss of firmness, synthesis of taste components). The effect of the ethylene concentration, temperature and time on product behaviour is well known qualitatively but no specific quantitative knowledge is available.

1.2 Mobile devices for ethylene measurement

Laboratory scale technologies like photo acoustics or gas chromatography offer a resolution that is accurate enough to detect even changes during the pre-climacteric state. Chapter 4 describes different physical measurement methods and relates their resolution to typical ethylene production rates. It discusses how cost effective devices could be developed that are suitable for mobile measurement in reefer containers or trucks.

1.3 Influence of harvest / pre-harvest conditions

Different harvest maturity conditions not only cause an offset in the keeping quality but also influence the sensitivity to temperature variation. Chapter 2 shows how a keeping quality model that incorporates the effects of time, temperature and harvest maturity affects transport scenarios for tomatoes.

1.4 Extended telemetric supervision for reactions in real-time

Telemetric supervision enables risk detection during transport to be communicated to the transport operator. This demands constant mobile communication. Companies like Danzas [Peil02, p. 246], IBM / Maersk[1] and Cargobull Telematics[2] work on telemetric solutions for supervision of transport vehicles. These systems go beyond standard tracking and tracing. They do not only query the location of the freight at any point of time, but query also the assessment of sensor data. On pre-defined conditions, like opening the doors at a wrong place or overstepping a temperature limit, a warning is sent to the freight operator. Unlike data loggers that need to be read out at arrival, these systems enable real-time risks assessment. Currently, remote monitoring systems are not equipped to assess the product quality and product supervision is limited to (mainly temperature) threshold checking.

1.5 Local processing

The transport operator is not trained to interpret sensor data that indicate quality changes. Therefore, pre-processing is needed either on a central server at the transport operators site or locally, during transport. For the first approach the vehicles have to send a full sensor protocol over the mobile network. The second option is based on local evaluation of the sensor data. This approach assumes that the vehicles are equipped with local processors. Comparable to Grid computing[3] the fleet supervision task is distributed among a network of local processors. The Grid approach is more efficient if the problem employs the processing of several independent data streams [Walt05], like local sensor information. Local pre-processing reduces the data volume that has to be transferred over the mobile network as well as the communication costs by a factor between 10 and 100. Instead of hundreds of sensor values only the resulting quality assessment needs to be transmitted. The communication rate is adapted automatically: On crucial quality losses a notification is send immediately. If no critical events are observed only one control message per day is sent. Shifting the processing to the origin of information increases the robustness of the system. Local processing units autonomously continue their supervisions task, even if the external network is unreachable. The extra cost for outfitting trucks or reefers with local processors needs to be weighted with the extra communication costs needed for a central server approach.

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[1] IBM press bulletin, see RFID-Journal http://www.rfidjournal.com/article/articleprint/1884/-1/1

[2] see product leaflet at http://www.cargobull.de/en/produkte_und_dienstleistungen/cargobull_telematics/Produkte/default.jsp

[3] The approach of Grid computing enables solving highly-complex problems by collaboratively employing unused computing resources of hundreds to thousands of PCs.

1.6 Mobility

The application of quality models in a transport network needs to be flexible in terms of the type of products that are transported and the ability to cope with tractability when freight is transhipped. The model accompanies the freight along the supply chain. Mobility means that if the fright is loaded to another means of transport, the model and its current state have to migrate to the next processor platform as well. Chapter 3 gives an overview of our technical implementation of quality models as mobile and local processes.

1.7 Multi disciplinary cooperation

The challenges of an adaptive supervision system for food transports cannot be met by a single specialised group. The data transport and sensor system group needs to cooperate with a product quality group. A multi disciplinary cooperation offers the chance to develop improved solutions for the supply chain.

The **Institute for Microsensors, -Actuators and -Systems** (IMSAS) at the University of Bremen (www.imsas.uni-bremen.de) participates since two years in a collaborative research centre on the autonomous cooperation of logistical processes [Freit04]. During this period a processor platform for integration into means of transport was constructed as part of an intelligent transport and route planning system. The other focus is research and development of MEMS (Micro-Electro-Mechanical Systems) and measurement systems. Under the Clean Air project a micro gas chromatography column [Stu05] was developed for measurement of volatile aromatic components in the ppb range (parts per billion).

The **Horticultural Production Chains group** (HPC) of Wageningen University (http://www.hpc.wur.nl/UK/) uses a systematic approach to describe and predict product quality of ornamentals, vegetables and fruits in the horticultural chain. The focus is to allow information acquired during the preharvest phase to become meaningful and available during the postharvest handling phase. A recent development at HPC is the combination of kinetic (quality) modelling and stochastic modelling to describe the behaviour of batches of products in the horticultural chain.

2 Dynamic quality modeling

Quality is a difficult property, as everyone uses a slightly different set of criteria to interpret the quality of a product. In order to have a practical grip on quality related issues, the concept of acceptability was introduced. When somebody decides on the acceptability of a product, the quality is compared to a criterion, the quality limit. If the quality exceeds that limit, the product is accepted, but otherwise rejected. Thus, acceptability of a product depends on product quality and on the level of the acceptance limit. The acceptance limit is primarily defined by economical and psychological factors; the quality of a product is largely defined by its intrinsic properties. Keeping quality is the time until the product attribute drops below the acceptance limit at any dynamic or static condition. So, keeping quality combines two aspects of product acceptance, the acceptance limit and product quality, into a generally applicable index of quality [Tijs96].

2.1 Keeping Quality for static conditions

Keeping quality provides information about the time the product can be kept prior to becoming unacceptable, but it does not provide information either about the actual state of the product's quality or about to the processes occurring in the product. Without information, however, about the mechanisms involved in the decrease in quality or quality attributes, the dynamics of keeping quality cannot be described. In practice the decrease of a single quality attribute can be often approximated by one of four basic types of mechanism as shown in **Figure 1**. It can be shown that for these mechanisms the keeping quality (KQ) is proportional to the inverse of the reaction rate constant of the quality decrease: KQ=f(Q)/k with f(Q) the quality function as described in **Table 1** (with Q_0, the initial quality, Q_l the quality limit and Q_{inf} the maximum quality at minus infinite time). This gives the opportunity to describe the behaviour of keeping quality as a function of temperature. All reaction rate constants are assumed to depend on temperature (T) according to Arrhenius’ Law [Arr1889] (Eq. 1):

$$k = k_{ref} \cdot e^{\frac{E_a}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \qquad (1)$$

with k_{ref} being the value of k at an arbitrary chosen reference temperature T_{ref} (in K), E_a the energy of activation (in $J \cdot mol^{-1}$) and R the universal gas constant ($8.314\ J \cdot mol^{-1} \cdot K^{-1}$).

In many horticultural products, the quality attribute that limits the acceptance by the consumer shifts from one attribute at a certain temperature to another attribute at another temperature. For the description of this more complex situation, let’s assume that the storage temperature remains constant during the whole storage period, but the quality attribute that limits the shelf life of the product, changes from one attribute to another depending on the level of the constant temperature. In tomatoes for example kept at constant temperatures below 8 ºC the limiting factor is usually chilling injury, above 15 ºC it is firmness. The extension to be made to the previous model is to determine which quality attribute is limiting at which temperature. Each separate quality attribute has to be described by its own reaction rate constant.

In the following equation, the keeping quality model incorporates multiple limiting quality attributes (1…N). The KQ is now described as a product specific KQ value at the reference temperature (KQ_{ref}) divided by the sum of the reaction rate constants that are adapted for the measurement temperature that represents the relative importance of the N^{th} quality process at reference temperature T_{ref} [Tijs96].

$$KQ = \frac{KQ_{ref}}{\sum_{i=1}^{N} k_{ref}(i) \cdot e^{\frac{Ea(i)}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T} \right)}} \quad \text{with} \quad \sum_{i=1}^{N} k_{ref}(i) = 1 \quad \text{at} \quad T = T_{ref} \tag{2}$$

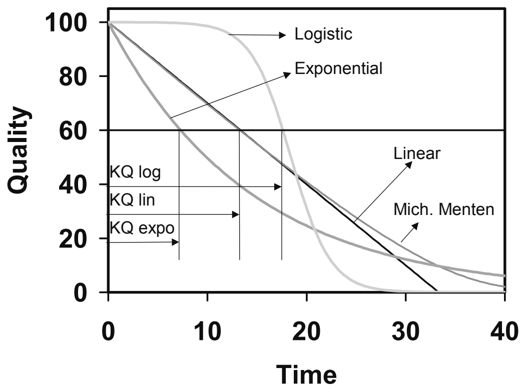

***Figure 1:** Decrease in quality for several types of mechanisms (arbitrary units)*

Mechanism	f(Q)
linear	$Q_0 - Q_l$
exponential	$\log_e\left(\frac{Q_0}{Q_l}\right)$
logistic	$\log_e\left(\frac{Q_{inf} - Q_l}{Q_l \cdot C_{ba}}\right)$

***Table 1:** Overview respective quality functions*

2.2 Keeping Quality for dynamic conditions

With a dynamically changing temperature acting on a decreasing quality, the remaining keeping quality at some standard temperature can be calculated for different time temperature combinations (scenarios). The remaining keeping quality is called shelf life and may be expressed at a temperature (T_{St}) that is convenient for a particular application.

The quality function f(Q) for each type of kinetics is the inverse function of the quality behaviour at constant temperature. Consequently, the keeping quality will change linearly during the (very small) time period during which the temperature can be considered constant. For each day of storage a certain fraction of keeping quality will vanish. The slope of the linear change will depend on the storage temperature as described by the combined reaction rate constant.

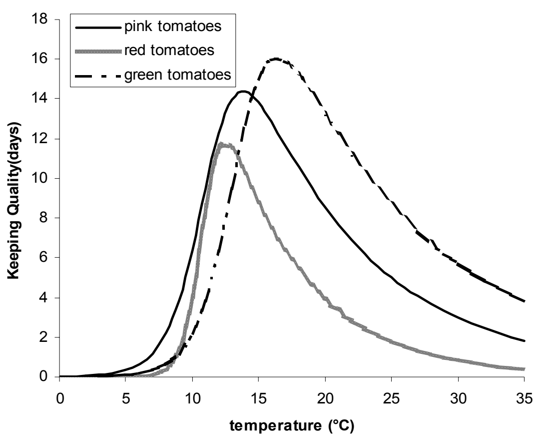

***Figure 2:** Keeping quality as function of temperature for green, pink and red tomatoes.*

Provided the quality limit remains the same throughout the storage period and provided the initial quality is the same as or comparable to the measuring situation, the dynamic model can be formulated as:

$$KQ = KQ_{ref} - \frac{\int_0^t \left(\sum_{i=1}^{N} k_{ref(i)} \cdot e^{\frac{Ea(i)}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T(t)} \right)} \right) \cdot dt}{\sum_{i=1}^{N} k_{(i)}(T_{st})} \qquad (3)$$

In its dynamic form, the keeping quality formulation of Eq. 3 predicts keeping quality as a function of temperature, initial quality and quality acceptance limits. Calculation of the dynamic model requires only one numerical integral. Due to the fast numerical integration of that one integral, optimization of distribution chains with respect to produce quality becomes economically feasible. The model accounts for the behavior of keeping quality of about sixty species of fruits and vegetables, including chilling sensitive products, over a wide range of temperatures [Tijs96].

2.3 Tomato Keeping Quality

In the case of tomatoes the following temperature dependence of the keeping quality (applying Eq. 2) can be derived for tomatoes varying in maturity and kept at a constant temperature. Data for pink tomatoes are taken from [Tijs96] and adapted for green and red tomatoes using higher (green tomatoes) and lower (red tomatoes) values for KQ_{ref} than the published value of KQ_{ref} that is used here for pink tomatoes. The temperature dependence shown in **Figure 2** indicates that at least two quality attributes are responsible for the KQ behaviour: at low temperatures tomatoes suffer from chilling injury, at high temperatures the KQ is limited by low firmness. Additionally, for green tomatoes there is an additional quality attribute that limits the keeping quality at low temperatures: green tomatoes need to ripen before the firmness and colour are acceptable.

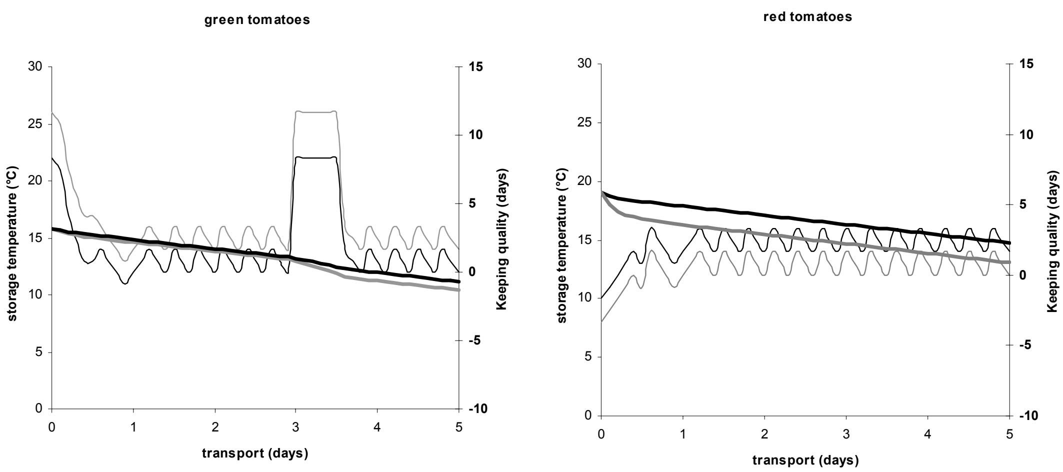

Figure 3: *Two scenarios for transport of tomatoes differing in maturity.*

Figure 3 shows the effect of dynamic temperature variations on the keeping quality (bold lines) of tomatoes varying in maturity. The left hand side plot shows the effect of starting with a relatively high temperature (in e.g. summer) and a breakdown of the cooling system during day 3 for green tomatoes on the keeping quality. The right hand plot shows the effect of starting with a relatively low temperature (in e.g. winter) for red tomatoes on the keeping quality. Also, the effect on the keeping quality is shown for temperature fluctuation (2 °C) due to the heating and cooling cycle in the truck or reefer.

2.4 Ethylene and Tomato Keeping Quality

Tomatoes produce significant amounts of ethylene, varying from 0.3 to 8 µl/(kg*h) depending on their maturity [Hoe02]. Interestingly, the ethylene production over time provides a clear indication of the maturity (green, pink or red). Green tomatoes will show an increasing ethylene concentration over time indicating the change from auto-inhibition of ethylene (pre-climacteric stage) to autocatalytic ethylene production (climacteric stage, ripening). Pink tomatoes will show a constant level of ethylene production and red tomatoes a sharp decrease of ethylene production [Hoe02]. This means that subsequent ethylene accumulation periods over time (e.g. six ethylene accumulation periods of 1 hour during a six hour period) can characterise the tomatoes in terms of their maturity. Combining this information with temperature sensor data enables the estimation of the expected keeping quality (as shown in Figure 3).

3 Technical implementation of dynamic quality models

The aim of our system is to apply quality models to supervise transports of perishable products. The keeping quality models, which were examined under laboratory conditions, have to be translated into a form that is suitable for transport. Sensor data have to be processed in real-time to enable adjustment during transport and of warehouse planning before the transport is completed.

For the technical implementation of the quality modelling we have selected the approach of software agents originating from artificial intelligence research [WoJen95]. An agent is a program that acts on behalf of its owner. Once started it is executed completely autonomously. The agent makes decisions based on observations of its environment. It can travel to different software platforms to accomplish its task.

The keeping quality models are part of a software agent that is responsible for the supervision of a corresponding freight item. It accompanies the batch along the supply chain. The supervision process is executed on a local platform inside the current means of transport, where it pre-processes sensor data and estimates the keeping quality. The agent provides the freight operator with an estimate of the keeping quality, the time until the product becomes unacceptable. The agent will update the estimation based on continuous sensor readings. When the earlier estimate is no longer valid due to changing transport conditions or more accurate estimation of the keeping quality due to more sensor data transport planning will be notified.

3.1 Combination of technologies

The technical system for autonomous transport supervision combines technologies from different fields like Radio-Frequency Identification (RFID), Wireless Sensor Networks (WSN), mobile and satellite communication, software agents and embedded processor platforms. Parts of these technologies have already been applied in tracing and tracing or telemetric remote supervision systems, but they have to be extended in some points.

RFIDs are not only used for tracking, but also to control the transfer of the software agent. To detect deviations in the temperature distribution inside a packed reefer container the sensor monitoring was extended to a network of wireless sensor nodes, which can be placed independently. Local temperature variations that result from bad thermal isolation or wrong loading procedures may have a large effect on the keeping quality. The agent will not so much answer requests for sensor data, but will initiate communication by itself when a crucial change in keeping quality is detected or a new freight is loaded. In the latter case the corresponding software agent is transferred over the communication network. The computational facilities of the system have to be extended to host the software agents. By optimisations in the framework the necessary processor hardware was reduced to a credit card sized module[4]. An overview of the sensor system was given by Jedermann [Jed06b].

3.2 Agent framework and auto-configuration of the supervision system

For efficiency reasons the sensors and processors to estimate the keeping quality are separated from the freight. This approach reduces the costs for partners in the chain to that of the purchase price of standard RFID tags. When a new product is loaded into a reefer or truck, the freight is linked to the supervision resources that are provided by the means of transport. This configuration process is controlled by data stored on the RFID tag. The truck or reefer agent automatically requests information from the freight agent belonging to the previous means of transport to enable continuous monitoring of the keeping quality in every part of the chain. If the product leaves the container, the agent is 'frozen' and send to the next vehicle. The migration process for software agents was described in detail by Jedermann [Jed06a].

The processor platforms have to provide a special software framework [Bell03] that is based on the JAVA programming language to execute the agents. The framework was adapted and optimised for embedded processor modules with limited resources [Jed06a]. We applied a new JAVA implementation [Sieb02] for embedded processors that allows running the same program code as on

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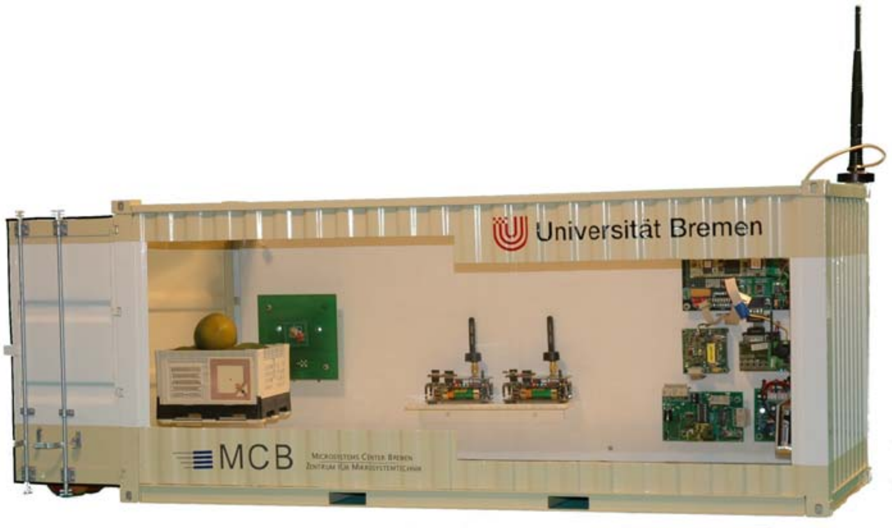
[4] Modules with an ARM XScale processor are offered between 100 and 250 Euros, see www.ssv-embedded.de for example.

PCs. The intrinsic feature of JAVA to dynamically reload parts of the program code allows for easy adoption of future types of quality models.

3.3 Prototype and demonstration scenario

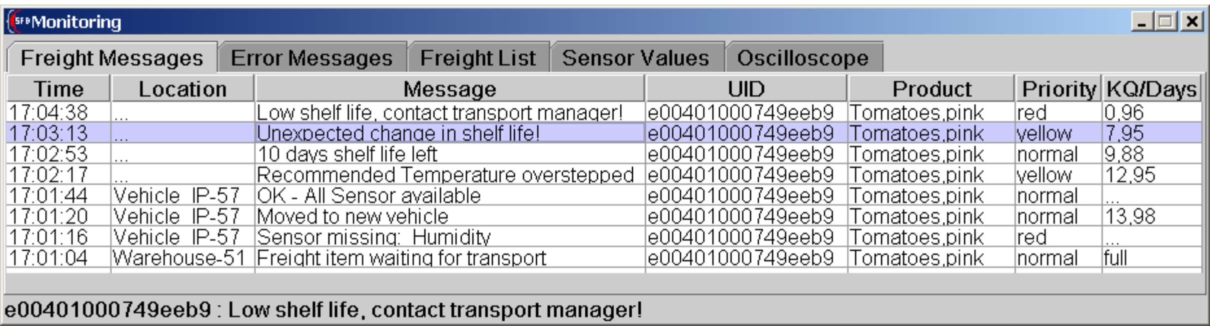
The required technologies were integrated into a reduced scale prototype shown in **Figure 4**. An external communication[5] unit automatically selects between different available networks like WLAN, UMTS and GPRS. The 'intelligent container' is linked to an autonomous route and transport planning system[6] [Jed06c].

__Figure 4:__ Reduced scale (1:8) prototype of the intelligent container. Loaded freight items are scanned by the RFID-Reader on the left. Sensor nodes supervise the environmental conditions[7] (middle). A processor module on the right side executes a software agent containing specific transport instructions and quality modelling. The module for external mobile communication is placed on the right side panel.



Our demonstration scenario starts with the definition of transport parameters by the sender. He fills an electronic consignment note with destination and special supervision requirements. In addition, information regarding the type of product is added as to inform the agent which quality model out of a database needs to be employed. Subsequently, the route planning system searches for a suitable vehicle in the pool of available transports. During transport the operator receives notifications on important events like transhipment of the product or problems at loading because of missing sensor equipment. **Figure 5** shows a typical event log. If the keeping quality drops below a pre-defined threshold, a warning is send to the freight owner or transport operator.

The priorities in food supply management are on-time delivery, followed by price level and quality. The costs for replacement purchases for products that have become unacceptable are considerable. Early notifications and predictions of quality changes could reduce these costs. A retail network may use the option of redirecting transports that are in a critical state to find costumers with less compelling demands with regard to product quality or a destination that can be reached in shorter time.


Monitoring

Freight Messages | Error Messages | Freight List | Sensor Values | Oscilloscope

Time	Location	Message	UID	Product	Priority	KQ/Days
17:04:38	...	Low shelf life, contact transport manager!	e00401000749eeb9	Tomatoes,pink	red	0,96
17:03:13	...	Unexpected change in shelf life!	e00401000749eeb9	Tomatoes,pink	yellow	7,95
17:02:53	...	10 days shelf life left	e00401000749eeb9	Tomatoes,pink	normal	9,88
17:02:17	...	Recommended Temperature overstepped	e00401000749eeb9	Tomatoes,pink	yellow	12,95
17:01:44	Vehicle IP-57	OK - All Sensor available	e00401000749eeb9	Tomatoes,pink	normal	...
17:01:20	Vehicle IP-57	Moved to new vehicle	e00401000749eeb9	Tomatoes,pink	normal	13,98
17:01:16	Vehicle IP-57	Sensor missing: Humidity	e00401000749eeb9	Tomatoes,pink	red	...
17:01:04	Warehouse-51	Freight item waiting for transport	e00401000749eeb9	Tomatoes,pink	normal	full

e00401000749eeb9 : Low shelf life, contact transport manager!

__Figure 5:__ Detail of the graphical interface: The window lists all warning messages for selected items including time stamp (time-lapse mode) unique identification number and current location. The column at the right hand side shows the estimated keeping quality.

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[5] ComNets Institute, University of Bremen
[6] Centre for Computing Technologies (TZI), University of Bremen
[7] The Sensor Nodes were designed by ITEM, University of Bremen

4 Ethylene sensors for improved quality models

4.1 Required resolution

The amount of ethylene (C_2H_4) emitted by climacteric products depends on the ripeness [Bia54]. The emission rates of ethylene range from 0.01 µl / (kg·h) to over 100 µl / (kg·h) [Scha05]. Based on this, Scharnow classifies fruits and vegetables into 5 groups (**Table 2**). Measuring the C_2H_4 concentration is important in order to monitor the entire ripening process. In the pre-climacteric phase of ripeness the amount of ethylene produced as well as the positive change of the ethylene production over the time are low. Shortly before the climacteric phase is reached, a strong increase of the rate of ethylene production can be seen. Decreasing rates indicate that the fruit is in the post-climacteric phase.

The following rough calculation estimates the needed sensitivities of ethylene measurement systems to consistently monitor the fruit's ripeness during transport: Using a 20 foot ISO-Container for fruit transport leads to a total free volume of 38 m³. The maximum allowable payload in this case is 21,5 t at 33 m³. Assuming the actual container payload is 80% of the maximum, the free volume would be 11,6 m³ and a load of 17,2 t. With an emission rate of 0,1 µl / (kg·h) the resulting ethylene concentration is about 150 ppb/h. For 40 feet ISO-Containers this value decreases to about 95 ppb/h under the same conditions.

This means that a system for measuring changes in ethylene concentrations during transport must have a sensitivity in the ppb region.

Ethylene exhalation	µl / (kg·h)
Pineapples	0.01 ... 0.1
Lettuce	0.1 … 1
Bananas (Climacteric)	1 … 10
Pears	10 … 100
Apples	> 100
Tomatoes[8]	0.3 … 8

Measurement Technique	Resolution
IR Absorption Spectroscopy (GoodFood Project, [Har05])	60 ppm
Electrochemical Cell (ICA-Storage, www.icastorage.com)	0.5 ppm
Chemiluminiscemce (Geo-Centers, www.geo-centers.com)	0.1 ppm
Miniaturised Gas-Chromatography (expected)	> 10 ppb
FID – Gas chromatography (AFC Int. Inc., http://www.afcintl.com)	0.1 ppb
Photo Acoustic Spectroscopy (Invivo GmbH, www.invivo-gmbh.de)	< 0.1 ppb

Table 2: Typical ethylene rates for different products (left hand side). The table on the right hand side shows the resolution of commercial ethylene measurement devices.

4.2 Measurement techniques and systems

High sensitivity ethylene measurement methods traditionally use Photo Acoustic Spectroscopy (PAS) [Gab98], Flame Ionization Detector Gas Chromatography (FID-GC) and the Chemiluminescence Method (CLM) [Gop92, Sko92, Hof04].

These traditional high-resolution methods (see right hand side of Table 2) can only be applied in under carefully controlled conditions. The application of these systems during transport is not cost effective and is not technical feasible due to the system complexity, size, maintenance requirements and purchase costs.

New mobile and cost effective measurement systems that are highly sensitive and selective are needed to detect ethylene in the ppb region. In addition to having a high sensitivity, these systems have to overcome the described disadvantages of traditional measurement systems. Overcoming these challenges is an important part of future research.

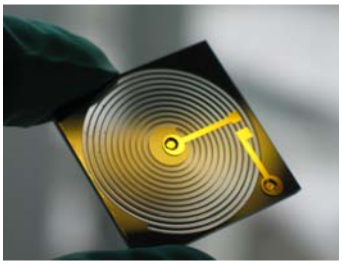

Figure 6: *Micromechanical fabricated GC-Column*

[8] *According to de Wild et. al. [deW05] and Hoeberichts [Hoe02].*

A promising approach is the use of commercially available miniaturized low sensitivity (ppm region) and selectivity ethylene sensors [Chen96, Zhang02, http://www.appliedsensor.com/] combined with new MEMS (Micro-Electro-Mechanical System) devices for analytical applications. Enhancing the performance of low sensitivity sensors can be achieved by the usage of miniaturised preconcentration devices. Based on the thermodesorption effect this device collects specific gas molecules over a specified time. When the gas molecules are released, the concentration in the collector is higher than the concentration in the environment and thus high enough to be measured by the low sensitivity sensor. The actual gas concentration in the environment can than be calculated through the characterised preconcentrator. An enhancement of the gas concentration trough a preconcentrator, by a factor of 5000 was achieved for different gases [Tian03]. To improve the selectivity of the sensors, miniaturized GC-columns will be used [Stur04]. **Figure 6** shows a miniaturised GC-column for separation of volatile organic components developed by IMSAS[9]. This design cannot be used for ethylene measurements directly because of the different chemical characteristics.

The function of these devices is similar to the function of GC-Columns used in FID-measurement systems. Their usage for an ethylene measurement system could lead to measurement resolutions of about 10 ppb. Compared to traditional measurement systems, the miniaturised system would be inexpensive, robust and nearly maintenance free.

5 Summary

5.1 Conclusions

Cooperation between IMSAS (University of Bremen) and HPC (Wageningen University) has produced a reduced scale prototype of an autonomous transport monitoring system that demonstrates the application of KQ-Models for quality supervision of tomatoes as example.

The sensor system provides a KQ-model with data to characterise the tomatoes and estimate the keeping quality, the time before the tomatoes become unacceptable for consumption. The KQ model is based on relevant processes that influence the keeping quality of perishable products such as chilling injury (at low temperature) and firmness (at high temperature).

To characterise the maturity of the tomatoes and adjust the model parameters, a measurement of the ethylene concentration change over time is necessary. Traditional ethylene measurement devices cannot be used during transport; a new ethylene device that is highly sensitive and selective, such as a miniaturised GC, has to be developed.

The technical implementation for the transport monitoring system pre-processes sensor data in real time on a credit-card sized processor. A software agent provides the freight operator with an estimate of the keeping quality and updates this estimate only when needed (e.g. changing transport conditions or a more accurate estimation of the keeping quality due to more sensor data) to prevent data transmission costs. To allow easy access in other parts of the horticultural production chain the KQ data are written on a standard RFID tag attached to the product.

5.2 Future work

The current cooperation between IMSAS and HPC needs to be extended in three areas before this system can be used in practice. The presented concepts for a mobile ethylene sensor have to be translated into a technical application in the first place. Secondly, experience needs to be gained to incorporate the current system into commercial telemetric and transport planning systems. Thirdly, the KQ model needs to be adapted for a range of other perishable products. This means that models need to be developed that can use other sensor data, such as relative humidity measurements. Also, the effect of ethylene on climacteric products needs to be accounted for quantitatively.

6 References

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