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Applying autonomous sensor systems in logistics—Combining sensor networks, RFIDs and software agents

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Abstract

New sensor, communication and software technologies are used to broaden the facilities of tracing and tracing systems for food transports. An embedded assessing unit detects from sensor data collected by a wireless network potential risks for the freight quality. The estimation of the current maturing state of agricultural products will be supported by measurements of the gaseous hormone ethylene as an indicator for the ripening processes. A miniaturized high-resolution gas chromatography is under construction. The system autonomously configures itself to a product specific supervision task based on data scanned by an RFID reader during freight loading. Mobile software agents accompany the freight along the supply chain. They pre-process the vast sensor data and submit only substantial changes to the freight owner.

Keywords: Wireless sensor networks; Autonomous agents; Logistical applications; Ethylene sensors

1. Introduction

The transportation of perishable goods and foodstuffs has become a very important branch of logistics. More than 50,000 reefer trailers are registered only in Germany [1]. This line of business is a vast application field for sensor systems. Since the end of 2004 monitoring of transport parameters is legally required by EU regulations. The technical progress of data loggers strides through three generations. The first generation devices allow the recipient only to read a measurement protocol after end of transport. But these standard devices do not comply with the requirements of “just in time” processes. Damaged goods are only discovered at their final destination, when it might be too late for an appropriate reaction. The next generation of radio data loggers, allowing “on-the-road” access to sensor data, brings an improvement. But they can either only perform a very simple task or the amount of sensor data and configuration effort increases in a way that it cannot be handled by manual work.

In this work we present our concept and our first prototype for a third generation sensor system, characterized by: (a) autonomous configuration, (b) on-the-road sensor access and (c) autonomous assessing and decision-making. To get best performance we combine technologies from the fields of RFIDs,[1] wireless sensor networks and software agents.[2]

Ultra low power sensor nodes were developed for wireless communication with prolonged service intervals. Our miniaturized gas chromatography system [2] for detection of volatile aromatic components[3] will be optimized for high-resolution measurements of the ripening indicator ethylene.

2. Fruit logistics as example application

Fruit logistics was chosen as an example because of its market importance. The predicted total sum of maritime transport of refrigerated products for 2005 is about 57.1 million tonnes [3]. More than the half of it (56%) is allotted to fruit transports. Furthermore fruits and vegetables are an outstanding example for quality changes during transport. Unlike meat products fruits

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[1] Radio frequency identification, an electronic “Barcode” with contact less interface.
[2] A form of artificial intelligence algorithms.
[3] The GC was developed under the CLEANAIR-Project as cooperation between IMSAS and CNR-IMM Sezione di Bologna, Italy.

still live after harvest. Parts of the maturing processes take place during transport. Changes in quality and degree of ripeness along the supply chain are the normal case, not an exception. Enabling permanent supervision of these changes leads to an improved control of the transport chain.

During transport fresh agricultural products are chilled to a temperature between 0 and 15 °C. Deep freezing is seldom applied because of major quality reductions. Time pressure is given by the fruits themselves. Bananas have to arrive at the costumer within 3 weeks. Strawberries have to be delivered in less than 3 days. By controlled temperature and atmospheric conditions these time windows can be stretched.

Commonly used quality indicators such as firmness, starch and sugar content, taste and colour are not suitable for automated supervision, because they need unpacking and manual handling of the fruits or they even use destructive methods. Our aim is to derive a quality index from values that could be permanently measured inside a packed transport. These are the environmental conditions like temperature and humidity and gaseous metabolism products like carbon dioxide and ethylene.

3. System overview

The project is part of a new collaborative research centre[4] in Bremen, Germany. About 40 scientists are working in the field of adapting autonomous cooperating processes in logistics [4]. The sensor system will be integrated in a self-controlled transport supervision that goes beyond today's tracking and tracing systems. The demonstrator will be completed at the end of the first phase of the collaborative project in 2007.

The scope for automated decisions ranges from sending a message to the freight owner over changing the route planning up to ordering a replacement delivery. Our autonomous monitoring system for means of transport (MOT) consists of three layers: the sensor nodes, an internal wireless network and the assessing unit. The assessing unit operates at one hand as a gateway to the external logistical network, but its main task is to deduce changes of good quality from measurement values.

4. Sensor nodes and network

To handle the necessary protocols the sensors were equipped with a low power MSP430 microcontroller. The new designed sensor boards provide build-in self-test facilities.

For a detailed assessment of stress exposed to the good, the environmental parameters cannot be regarded as position independent. Especially the temperature may vary for a critical value. Locally freezing of the freight can cause major quality losses. This can happen due to improper adjustment of the freezer aggregate or blocking of the cooling air stream due to wrong packing. In extension to American regulations with four required temperature sensors, we implement a wireless sensor network (WSN) to monitor the gradient of different environmental parameters.

Besides secure communication the reduction of energy consumption is the most appealing challenge in designing wireless sensor networks. The service intervals for the battery powered sensor nodes should extend over several months. Measurement of slow changing parameters like temperature, humidity and illumination is not critical. These parameters can be monitored with an energy consumption of less than 1 mAh per month by interval measurements [5]. For the microcontroller that remains most of the time in power down mode about one additional mAh has to be added. Rapid changing parameters like acceleration/shock require constant measurement. For acceleration we have chosen the Star ACB302 sensor [http://www.starmicronics.com] with 72 mAh per month.

In order to reduce the power consumption of the wireless network we make use of the new IEEE standard 802.15.4, which is the base for the ZigBee protocol. But even with this ultra-low-power standard the communication is more expensive than taking a measurement. The communication rate has to be reduced to less than one message per minute on average.

The rate is adaptively controlled by the actual measurement value and the specific requirements of the monitored goods. In close proximity to critical values the sensor node reports even small deviations. In save regions only major changes are communicated. With the Chipcon CC2420 RF Transceiver the power consumption is about 2.5 mAh per month for an average rate of one message per minute. The owner has at any time access to each good and its state by a mobile connection.

5. Gas sensor for ethylene

For agricultural products the gaseous hormone ethylene is the most convincing indicator for stress exposed to the crop. Gäbler [6] found a distinct relationship between time dependency of the gas concentration and remaining quality at examinations of lettuce and other fruits.

During the maturing process nearly all plants exhale ethylene. Neighbour plants react to this gas by initiating ripening and ethylene production themselves. This can lead to a chain reaction where one overripe fruit can spoil hundreds of tonnes if they are connected to the same closed loop air stream. Especially

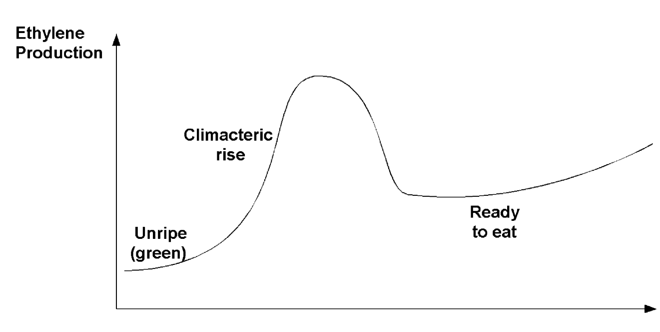


Fig. 1. Schematic course of the ethylene production over time for climacteric fruits.

[4] Collaborative Research Area Autonomous Cooperating Logistic Processes: http://www.sfb637.uni-bremen.de/.

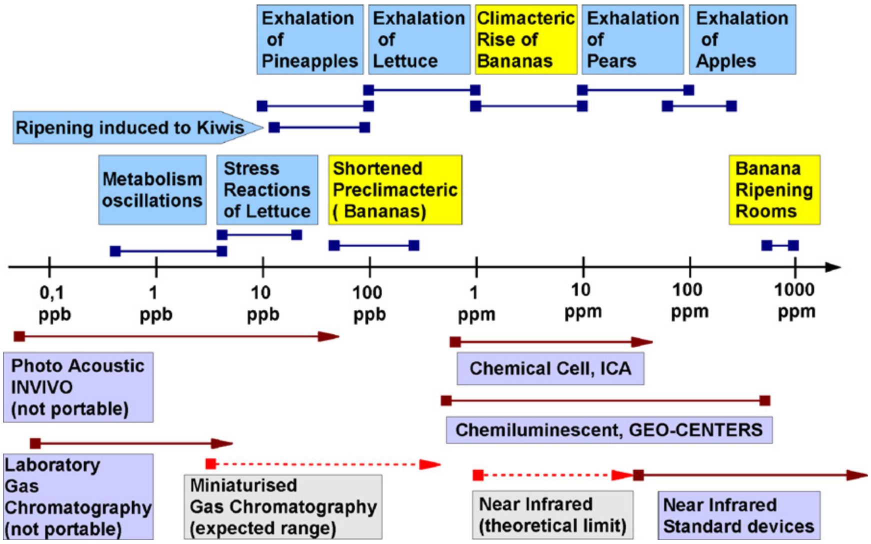


Fig. 2. The ethylene scale: the exhalation of fruits (upper half) is compared against the range of available measurement devices (lower half).

merging of crops with different ethylene rates and sensitivities is problematic.

Ethylene monitoring devices are often implemented in banana storage rooms and transports. Their ethylene production rate is high enough to be measured by state of the art instruments. Furthermore bananas have a distinct climacteric[5] rise that marks be beginning of the maturing process. A peak in the ethylene breathing accompanies the transition from the "green" unripe to "yellow" ready to eat state (see Fig. 1). In special ripening rooms the maturing is forced by admixturing ethylene to the atmosphere.

6. The ethylene scale

To monitor other fruits than bananas the measurement range has to be expanded. The ethylene exhalation of different kinds of fruits varies by a factor of more than 10,000. Fruits and vegetables are grouped in 5 decades. The ethylene production rate ranges from 0.01 μl/kg h to over 100 μl/kg h. For a typical packed container[6] 1 μl/kg h results in a gas concentration of 1 ppm (parts per million). Fig. 2 shows the ethylene rates and sensitivities of some typical fruits and vegetables according to Scharnow [3, p. 259]. The figures are given as an estimated range. According to Gowen [7] the preclimacteric phase of bananas is shortened by an ethylene level in the atmosphere of 0.1 ppm.

Oscillations in the plants metabolism and stress reactions at the lower end of the scale can be measured with precise laboratory instruments. With the photo-acoustic method implemented by the German company INVIVO [http://www.invivo-gmbh.de] it is even possible to detect a single caterpillar chewing on a lettuce leave by ethylene measurement [8].

At the ethylene scale there is huge gab between immovable laboratory devices and portable instruments. Market available portable systems provide a maximum resolution of 0.5 ppm. Various physical effects are used for ethylene detection. The British Company ICA-Storage uses a solid electrochemical cell [http://www.icastorage.com]; the chemiluminescent effect is used by Geo-Centers, USA [http://www.geo-centers.com]. The theoretical limit for Near-Infrared-Spectroscopy (NIR) is about 1 ppm, but commercial devices reach only a resolution of 20 ppm or more [9]. These methods suffer from cross sensitivities to CO (e.g. exhaust fumes), CO_2 (crop metabolism) and H_2O (humidity).

7. Development of a miniaturized gas chromatography

The estimation of quality changes during fruit transports needs a resolution in the rage of ppb to cover preclimacteric states and typical stress reactions of various agricultural products. On the other hand the possible costs and size of such a device a very limited for a practical implementation.

Gas chromatography is a well-established and very sensitive method for trace gas detection. The method may be miniaturized. Micro-GC's have been demonstrated by the IMSAS [2] for a number of gases such as toluene, xylene and benzene, which can be resolved in the ppb region. By optimization of surface chemistry and geometrical properties the chromatographic column could be adapted for ethylene detection. A calculation of absorption has been carried out with the result that a resolution of 1 ppb is achievable. A microtechnology based GC that is small and cost effective enough for permanent monitoring of containers and transport vehicles is under research.

8. Assessing unit

The freight owner is rather interested in statements about freight conditions than in detailed sensor information. Dynamic transport and route planning needs assessments of the following factors:

[5] From the Latin climactericus – turning point, critical time.

[6] Considered for the following example 20 feet container. Freight: 20 tonnes of fruits, free air volume: 20 m^3, ventilation rate: 1 per hour.

- Current quality state of the good.
- Remaining logistical time window to decide whether it is still possible to deliver the good in perfect condition.
- Acceleration factor for maturing processes to indicate the stress caused by deviations of the environmental parameters or contamination by microorganisms.

A general model for the dynamics of quality loss in dependency of temperature and humidity was introduced by FriLLog [10]. But parameterized models could be hardly found in the literature. Only Berruto et al. [11] describe a model for the firmness of peach. The firmness is obtained by a weighted integral of temperature, the deficit vapour pressure and the elapsed time. These models do not measure the quality of the fruit itself; they only predict quality changes in dependency of the environmental parameters. The accuracy could be improved if a factor is used that is directly associated to the internal metabolism processes. Especially changes in the ethylene rate could be used to correct the actual state of the quality model. Further research on dynamic quality models is necessary.

The vast information requires automated processing. The communication with the container might break down during transport. Costs of mobile or satellite communication have also to be considered. For these reasons the pre-processing of the sensor values is done locally by the “assessing unit”, an embedded system mounted inside the means of transport. Only major changes of the freight condition are reported to the outside.

9. Autonomous configuration

The demands on the sensor system change at each new transport. First the number of available sensors may change with the loaded freight. The list of possible radio connections between the sensor nodes is dependent of the packing and may also vary during transport. The network tree structure has to be updated without human interaction. For the distribution of the measurement task over the sensor network battery state, tolerances, position and reliability have to be considered. Sensor tolerances and faults should be compensated automatically. The network should be configured in a way to get all necessary data with the least possible energy consumption.

And secondly the assessing unit has to adapt to the special freight requirements at each transhipment. The unit does not know in advance how a certain good has to be supervised. The freight owner might even give the good an individual transport instruction on its way. In the further course of the project the task of the assessing unit will be extended to plan appropriate reactions to endangerment of the freight.

10. RFID and parallel information stream

Freight items are identified by a unique number (UID) stored on an RFID label. On one hand it is desirable to save all freight information and the complete sensor protocol on the label. But in practice a lot of restrictions have to be considered. RFID systems still do not comply with the wishes of transport companies. UHF readers are able to detect a label in a distance up to 3 m but they cannot penetrate materials containing metals or moisture.

Tags can only be accessed during loading and unloading. New UHF technologies loosen the limits for storage size and transfer rate, but the risk that changed data get lost during rewriting at unloading is still present. All critical data have to be transmitted over a reliable network. Besides the UID number the tag contains only selected duplicate information for quick access. If this information gets lost, a backup can be retrieved from the network. The freight state, the assessing function and reaction schemes are transmitted in a parallel information stream. This electronic consignment note accompanies the real object.

11. Technical implementation

In our prototype we make use of a 13.56 MHz reader from Feig Electronic [http://www.feig.de]. The effective data rate of the ISO 15693 protocol including overheads is less than 1 kbit per second. To avoid prolonged access times we restricted the amount of data stored on the tag to 64 bytes. Experiments resulted in 200 ms for data reading at the loading process and 400 ms for rewriting changes at unloading. To extend the reading range and speed up the data transfer we will switch over to UHF readers that are now available for the European market.

The hard- and software for the assessing unit was chosen to comply with the following needs:

- Sufficient calculation capacity for pre-processing and network configuration.
- Ability for dynamically loading of assessing functions.
- Integration into the means of transport. Limits in costs, size and power consumption have to be considered.

The ARM7 family provides a good relation between speed and power consumption. In our prototype we used Intel’s StrongARM consuming 1 W at a clock rate of 200 MHz. Two further ARM9 derivates are under test: Intel’s XScale and NetSilicon’s NS9750.

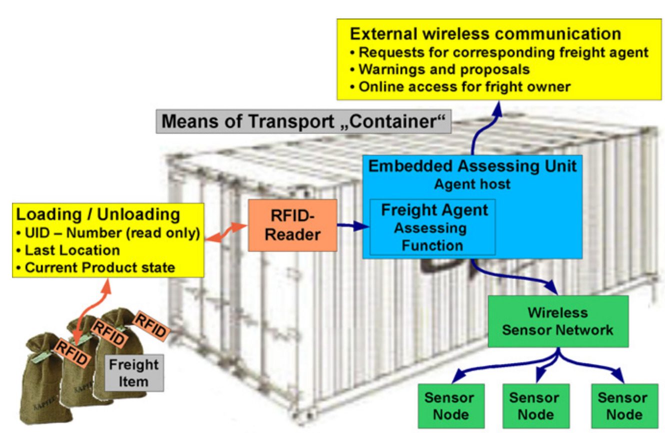
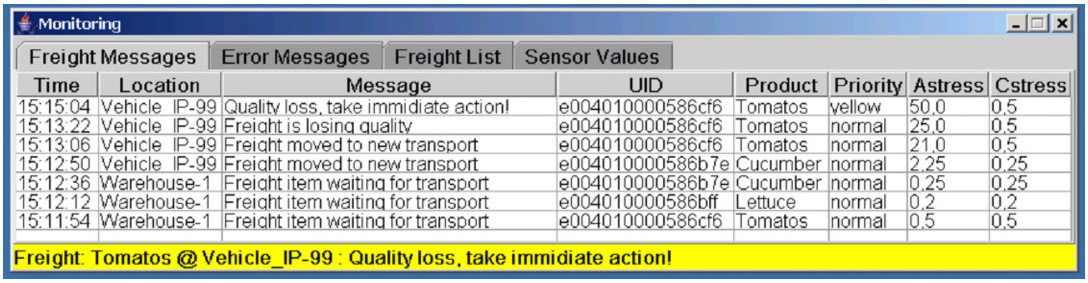


Fig. 3. Components of our system: at loading the identification number and the current product state are read from a label attached to the freight. The supervision agent accesses the wireless sensor network and sends warnings over external communication.



Monitoring

Freight Messages | Error Messages | Freight List | Sensor Values

Time	Location	Message	UID	Product	Priority	Astress	Cstress
15:15:04	Vehicle_IP-99	Quality loss, take immidiate action!	e004010000586cf6	Tomatos	yellow	50,0	0,5
15:13:22	Vehicle_IP-99	Freight is losing quality	e004010000586cf6	Tomatos	normal	25,0	0,5
15:13:06	Vehicle_IP-99	Freight moved to new transport	e004010000586cf6	Tomatos	normal	21,0	0,5
15:12:50	Vehicle_IP-99	Freight moved to new transport	e004010000586b7e	Cucumber	normal	2,25	0,25
15:12:36	Warehouse-1	Freight item waiting for transport	e004010000586b7e	Cucumber	normal	0,25	0,25
15:12:12	Warehouse-1	Freight item waiting for transport	e004010000586bff	Lettuce	normal	0,2	0,2
15:11:54	Warehouse-1	Freight item waiting for transport	e004010000586cf6	Tomatos	normal	0,5	0,5

Freight: Tomatos @ Vehicle_IP-99 : Quality loss, take immidiate action!

Fig. 4. Detail of the graphical interface for the owner: the window lists all warning messages for selected items including time stamp (time-lapse mode) and current location. The embedded unit calculates stress resulting from deviations of the optimal transport conditions. The current and the accumulated stress are displayed as percentage value.

There is still work to do at the wireless sensor network; especially the problem of localization of the nodes inside the container has not been solved yet.

12. Software

The selection of the programming language was driven by the need to execute platform independent dynamic code for the transport instructions. JAVA supports this feature but has hardly been used on embedded systems. The new Jamaica environment allows even real time applications under JAVA without stalls by garbage collection [12]. With JAVA it is possible to download and execute the code of the assessing function. This process resembles the loading of applets from Internet pages.

In our solution we implemented a concept that goes beyond downloading dynamic code. Programs that are already in the state of execution have to be transferred. The used mobile software agents are a special software construct that performs a defined task: for example the freight supervision on behalf of the owner. Several hosts unite to form an agent platform. Within this platform agents communicate independent of their current location. A simple command transfers an agent with its program code and current state to another processor. The new location could be the assessing unit of the next means of transport or a warehouse.

This JADE[7] framework was developed in a former EU-Project. We adapted this platform to a JAVA environment that supports processors from the ARM family.

Tests with our system prototype demonstrate that it is feasible to apply even a “luxury” framework like JADE to embedded systems. Only JADEs mobility mechanisms have to be downsized. The current method causes delays by transferring the complete class graph with more than 20 subclasses. By taking the advantages of object orientated programming only changes toward a library of predefined parent functions have to be transmitted.

13. The monitoring process

The producer or manufacturer of the good starts the supervision agent and defines how sensitive the agent reacts to sensor deviations. The agent connects himself with the sensors of the warehouse to start the monitoring. The processes that take place when the good is loaded into a means of transport with autonomous monitoring are summarized in Fig. 3. New freight items are detected by an RFID reader mounted at the vehicle door or at the loading platform. The UID, the kind of good and the address of the last known agent location are picked from the tag. With this information the embedded assessing unit requests the corresponding freight agent. The agent with the assessing function continues his work on the local processor. Based on values retrieved from the wireless sensor network he estimates the current stress for the freight item.

Warnings and recommendations are sent through the external network. This could be as in our prototype the WLAN of a transhipment point or a cargo ship. If the vehicle leaves the range of the local network, a satellite or mobile communication has to be used. At unloading the location address and changes of the freight state are written back to the tag. The receiver could easily scan the product quality with a handheld reader. The owner can watch all freight messages concerning his consignments by a graphical interface (Fig. 4). He can also send requests to the means of transport for the current freight state and sensor conditions.

14. Conclusions

Autonomous decisions enable fast reaction times to violation of specified sensor limits without human delays. The separation of sensors and identification tags allows full room monitoring without the need to apply expensive sensor notes to each transport item. The system can be easily expanded to special sensor requirements.

In a few years time the use of RFID-Tags on transport items will be a standard in logistics. It is a logical step to use these available tags for sensor configuration. There is a great challenge in modern logistics to broaden tracking and tracing by extensive sensor facilities.

Acknowledgements

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[7] Java Agent DEvelopment Framework: http://jade.tilab.com/.

References

[1] J.P. Peilsteiner, G. Truszkiewitz, Handbuch Temperaturgeführter Logistik, 1st ed., Behr's Verlag, Hamburg, 2002, p. 12.

[2] J. Stürmann, W. Benecke, S. Zampolli, I. Elmi, G.C. Cardinali, W. Lang, A micromachined gas chromatographic column to optimize the gas selectivity for a resistive thin film gas sensor, in: Proceedings Transducers XIII, Seoul, Korea, June 6–9, 2005, pp. 2083–2086.

[3] Y. Wild, R. Scharnow, M. Rühmann, Containerhandbook, vol. 3, 1st ed., Gesamtverband der Deutschen Versicherungswirtschaft e.V. (GDV), Berlin, 2005, p. 23.

[4] B. Scholz-Reiter, K. Windt, M. Freitag, Autonomous logistic processes: new demands and first approaches, in: Proceedings of the 37th CIRP International Seminar on Manufacturing Systems, Budapest, Hungaria, May 19–21, 2004, pp. 357–362.

[5] R. Jedermann, C. Behrens, C. Gorecki, D. Westphal, J. Congil, R. Laur, W. Benecke, W. Lang, Linking RFIDs and Sensors for Logistical Applications, Sensor 2005, in: Proceedings of the 12th International Conference, vol. 1, Nuernberg, Germany, May 10–12, 2005, pp. 317–322.

[6] R. Gäbler, Produktqualität von Obst und Gemüse, 10. Frische- und Lebensmittel-Logistik-Tagung, Krefeld, Germany, June 23, 2005 (oral presentation).

[7] P. John, J. Marchal, Ripening and biochemistry of the fruit, in: S. Gowen (Ed.), Bananas and plantains, Chapman & Hall, London, 1995, p. 436.

[8] R. Gäbler, Aufbau eines transportablen photoakustischen Spektrometers für den empfindlichen und kontinuierlichen Ethylennachweis in der Pflanzenphysiologie, Dissertation, Bonn, 1998.

[9] S. Hartwig, J. Hildenbrand, M. Moreno, J. Fonollosa, L. Fonseca, J. Santander, R. Rubio, C. Cané, A. Lambrecht, J. Wöllenstein, A highly sensitive IR-optical sensor for ethylene-monitoring, in: Microtechnologies for the New Millennium, Sevilla, Spain, May 9–11, 2005.

[10] P.M. Pastors, Allgemein gültige Prinzipien des Qualitätsverlust- bzw Verderb-Verhaltens von Frische-Produkten und (leicht-) verderblichen Lebensmitteln und die Konsequenzen für das 'logistische Fenster', vol. 1, ZGFLL, Krefeld, Germany, 2004, pp. 1–14.

[11] R. Berruto, P. Gay, C. Peano, Hybrid modelling for fruit quality prediction, in: L.M.M. Tijskens, H.M. Vollebregt (Eds.), Supply Chain Networks, Acta Horticulturae: Technical Communications of ISHS, vol. 604, International Society for Horticultural Science, Wageningen, The Netherlands, 2003, pp. 137–144.

[12] F. Siebert, Hard Realtime Garbage Collection, aicas GmbH, Karlsruhe, Germany, 2002, pp. 33–39.

Biographies

Reiner Jedermann finished his Diploma in Electrical Engineering 1990 at the University of Bremen. In Paderborn he worked as research associate in a project on embedded speech processing. During his employment at the German company Spectral Design he developed signal processor systems for audio applications. Since 2004 he is responsible for the development of intelligent sensor systems for freight containers. The project is part of the collaborative research centre 'autonomous logistical processes' at the University of Bremen.

Walter Lang studied physics at Munich University and received his Diploma in 1982 on Raman spectroscopy of crystals with low symmetry. His PhD in engineering at Munich Technical University was on flame-induced vibrations. In 1995 he became the head of the sensors department at the Institute of Micromachining and Information Technology of the Hahn-Schickard Gesellschaft (HSG-IMIT) in Villingen-Schwenningen, Germany, working on microsensors for flow, angular rate and inclination, sensor test and modelling. Februar 2003 Walter Lang joined the University of Bremen. Together with Wolfgang Benecke he is heading the Institute for Microsensors, -actuators and –systems (IMSAS) in Bremen.