The Intelligent Container
A Cognitive Sensor Net for Fruit Logistics

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Abstract: The Intelligent Container is a wireless sensor network for the control of perishable goods such as vegetables, fruits or meat. Several data interpretation tools are implemented in the sensor nodes. These can estimate temperature related quality losses, supervise sensor deployment and measurement intervals, and detect malfunctioning sensors. In order to retrieve information about the ripening directly from the transported fruits, the ripening indicator ethylene is detected using a newly developed highly sensitive and selective gas measurement system. The intelligent container allows the realisation of the new logistic paradigm of *dynamic* FEFO (First Expire First Out): the remaining life time—estimated shelf life—of the transported fruits is used to control the logistic process. This paper describes the developments performed on the Intelligent Container by the University of Bremen and its partners.

1 INTRODUCTION

In fruit logistics up to 35% of the cargo is lost during transport (Scheer, 2006). Only 5% loss is attributed directly to transport processes, but a large amount is lost indirectly due to insufficient conditions on the way, especially due to insufficient cooling and temperature control. It is known that within a reefer there may be temperature differences of several degrees from bottom to top, but today in most systems temperature is measured by only 2 temperature sensors. This way, large temperature gradients may easily be overlooked. A better control of the transport conditions due using Wireless Sensor Networks will allow a considerable improvement of transport quality.

Generally, fruits do not have sell-by date imprinted on the package, but the quality is estimated by the customer when he or she buys it. Often, fruits cannot be sold any more and have to be disposed of, it also may happen that a reseller rejects accepting a load after opening it. To control the transport process continuously would have a number of important advantages:

- When in time data about the specific load of a container are available, logistic processes may be re-adjusted accordingly and losses can be minimised. E.g. when it is known that a specific container with banana from Central America has a "hot spot", this container can be processed first to save as many fruit as possible (FEFO).
- Often containers are directly forwarded from the ship to the reseller without opening them. When the reseller refuses to accept, this is high cost for the wholesale dealer in terms of money and reputation. This situation may be prevented if sensor information is available. The rotting fruit are stopped and replacement can be launched instantly.
- In case the cargo of a container is known to be lost, there is no use in transporting it further on and in paying customs duty.
- When the state of the fruit at unpacking indicates a quality problem on the farm, there will be already two ships on sea with the same quality problem. If we had a sensor warning us two weeks earlier while the fruit are still travelling over the Atlantic ocean, we could inform the farm immediately and take action there.
- In some cases of fruit logistics counteraction during transport is possible, such as lowering the temperature set point of a reefer.
- For chilled and frozen food a proof of an uninterrupted cold chain is demanded by the authorities and by the customers.

Considering the market volume of fruit worldwide,

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reducing the loss by only a fraction of a percent means a considerable win in terms of money, and, furthermore, in terms of carbon dioxide footprint.

In logistic planning the paradigm applied is FIFO: First in – first out. Fruit which come first are moved on first. With the availability of sensor data, this paradigm might change to the new paradigm of *dynamic* FEFO: first expire – first out. The task is to estimate time before decay, the "remaining shelf life". Then, the fruit with short remaining shelf life are moved on first and to near bydestinations. The fruit with longer shelf life are moved secondly and attributed to longer distances. The fruit with expiring shelf life finally are stopped this way avoiding unnecessary transport. The shelf life estimation can be done by a decision support tool implemented in the sensor net. The term *dynamic* reflects the fact, that the remaining shelf life is continuously re-estimated according to the development of the fruit within time.

The advantage of FEFO compared to FIFO was verified in several studies. Koutsoumani (Koutsumani, 2005) calculated the probability density functions for the duration of local and international transports and temperature in retail shelves or customer refrigerators based on field studies. A simulation combined the resulting temperature curves with a biological model. The study showed that the share of products arriving at a critical bacteria load could be reduced from 16% to 8.2% by the FEFO approach. A similar study by the same group for seabream resulted in a reduction of losses from 15% to 5% (Tsironi, 2008). A study on strawberries by the University of Florida [Jedermann, 2008] showed that losses can be reduced from 36.9% to 22.8%. In summary, a delivery planning based on remaining shelf life can avoid between 8% and 14% of losses compared to planning without use or availability of quality information (Fig. 1).

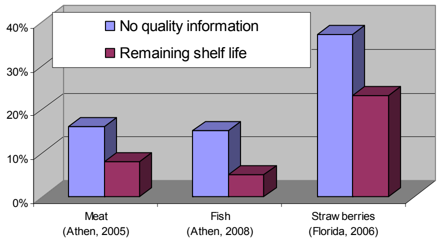

Figure 1: Case studies for product losses due the quality defects for FIFO (no quality information) and FEFO (based on remaining shelf life) planning.

To bring these features into reality, the "Intelligent Container Project" has been initiated (MCB, 2013). The research started in 2004 as a research project of Bremen University founded by "Deutsche Forschungsgemeinschaft".

In 2008 a transfer project was initiated in cooperation with two logistic partners: Dole Fresh Fruit Europe doing fruit transport on sea and Rungis express doing road transport. As an industrial technical partner, the trailer company Cargobull Telematics was a member of the consortium. First field tests on sea and land were performed. This research work was followed by a broad cooperation of industry and university, the "Innovation Alliance for the Intelligent Container", founded by the Federal Ministry of Education and Research of Germany. The Alliance for Innovation has been running from 2010 to 2013. In this paper we will discuss the most important results and findings of these projects.

2 THE SENSOR NETWORK

2.1 Layout of the Measurement Task

What tasks must this sensor net perform? When looking closer, the list of tasks to do becomes long and challenging. Fig. 2 shows the information flow within the system.

2.1.1 Quantities to Be Measured

Concerning quantitites to be measured, the first task is temperature. Today, 2 or 3 temperature sensors are usually used in a reefer. We deployed a number of 40 for test and we found that the temperature variation in reality is much larger than expected.

On the other hand, 40 sensor nodes per container are not a realistic scenario for practical application in every container. This way, the path has to be from 2 to 40 and then back to 12 again. Then, with the improved knowledge how to locate the sensors, interpolation can be done to calculate the whole temperature profile. This way, the systems also need data interpretation tools such as numerical models to estimate the development of a 3D-model of the temperature distribution from a few measurement points.

Temperature is by far the most important variable to be measured. In transports of 'dry' agricultural products humidity is important, since relative humidity must be kept below 75% to prevent the growth of mould fungus (Scharnow, 2005). Mould is a major danger when transporting berries and grain. Grain is highly hygroscopic, this way a container with grain will contain tons of water. Now imagine a container placed on the top of a vessel in a cold night in northern Atlantic. The average temperature in the container is 15°C, the average relative humidity is 60%, "on the safe side". Practically, at side exposed to the wind, the temperature is only 5°C, relative humidity rises to 100% and condensate will drop down on the grain, causing locally major mould fungus danger. This situation will be overlooked if only one humidity sensor is applied and no advanced data analysis is performed.

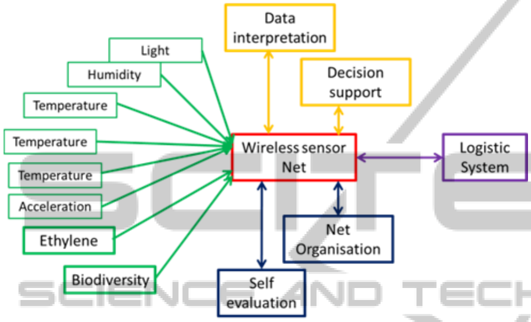

Figure 2: Information flow within the Intelligent Container.

In fruit logistics, the primary focus is temperature. Other important sensor functions which are needed for some transports are acceleration for shock detection and light. Though they are important, they cannot be covered in extenso in this paper.

2.1.2 Decision Support Tools

To estimate the remaining shelf life from the data, decision support algorithms have to be developed and implemented. Knowing the temperature history, these tools may estimate the change of the fruit with time. It soon turned out, that analysing a development is useful only if we know the starting point. What is the status of the fruit when loaded? Unfortunately, the biodiversity at loading is high. A major parameter is the weather before harvest. If there is rain before picking, the fruit will take up more water. A second important influencing factor is the transport from the farm to the port. Due to shaking on bad roads and fot the lack of cooling within a few hours in a truck fruit may lose days of shelf life. The status at packing is normally estimated visually by experienced operators during packing. In the case of bananas, colour patterns with different appearances—more green than yellow—are used in the port. Within the project of the Intelligent Container the company ELBAU (http://www.elbau-gmbh.de/) has developed an optical system to automate this analysis.

So far, during transport we only look at external data, such as temperature. Can we get information about ripening from the fruits themselves? Actually the process of ripening of fruits is correlated with the emission of ethylene gas. This way, measuring the indicator ethylene gas, a direct observation of the ripening and decay is possible. These developments are described separatly in section 3.

2.1.3 Management of Sensor Nodes

The sensor net does not only look at the container and the fruit, it also observes itself for management of the sensor nodes and for failure detection.

The system can supervise and change its own deployment. How many sensors do we need? What distance between the sensors can we allow? These questions can be analysed looking at the correlation of the data of different sensors using a method developed for geostatistics by D.G. Krige (Krige, 1951) and now transferred to sensor nets (Jedermann, 2009). During transport sensors cannot not be removed, but they can be put to sleep this way augmenting the life time of the batteries. The sensor nodes measure their remaining energy; the routing may be changed in the way to allow nodes with weak batteries to sleep (Behrens, 2007). Also the dynamic behaviour of the temperature is analysed to adapt the duty cycle to the situation. Slow development can be answered with a reduction of the measurement cycle to save energy (Wang, 2010; Wang, 2011).

2.1.4 Self Evaluation

A last and complicated task is the self-evaluation. Imagine a sensor node shows anomalous humidity values at some point: is the sensor node defect or is there an anomaly, such as a broken can? To analyse divergent behaviour a neural network has been developed (Jabbari, 2009).

Fig. 2 gives an overview of the capabilities of the sensor net. Within the Intelligent Container Project, we decided to implement the important parameters within the sensor nodes. An alternative approach would be to communicate the data and to calculate models on a higher level, E.g. in a master node. Our experience is that this approach will not give us the robustness we need. In an extremely challenging surrounding such as see transport, failure of a node is always possible. The system must be able to rearrange if a node fails, and the maximum robustness will be achieved if we implement the important algorithms locally, even if this means that we have to apply several parallel nodes which are able to calculate the models.

In the following paragraphs, some of these aspects will be discussed in detail.

2.2 The Sensor Net

The communication system of the intelligent container consists of the internal wireless sensor network, the external network for remote access to the container, and a gateway to bridge between these two networks. Whereas the external network can be implemented by standard components and commercially available networks, such as the Iridium satellite system or cellular mobile networks, the internal networks requires specifically adapted solutions, and thus be discussed in detail.

Most wireless sensor node devices operate in the 2.4 GHz range according to the 802.15.4 standard. Our prototype sensors are based on the TelosB from Crossbow (2005). They were mounted into a IP67 water tight housing with an SHT75 external temperature and humidity sensor.

In contrast to other sensor network applications in buildings or farming setups (Ingelrest 2010) with a typical communication range between 10 and 100 meters, the range dropped to 0.5 meters, if the sensors were packed into banana pallets (Jedermann, 2011). The network protocol must be able to find routes in a sparsely connected network (Becker, 2009). In contrast to other applications, the data volume is very low. Only 6 bytes are required in addition to addressing and protocol overhead to transmit temperature, humidity and battery voltage measurements.

The energy consumption of the sensor nodes mainly depends on the radio, which draws approximately 20 mA in both receive and transmit modes. The MSP430 micro controller requires only 1 mA in full operation and 1µA in sleep mode. The active radio time should be reduced as much as possible.

For our field tests, we developed a communication protocol, the “BananaHop Protocol” (Jedermann, 2011). It requires an active radio time of 5 seconds to transmit its own data and forward those of other sensors per measurement frame of 150 seconds, equivalent to duty circle of 3.3%. The duty circle can be further reduced, if the measurement intervals are prolonged.

Only if a sensor loses the synchronization the duty circle increased to 50% because the sensor has to listen for an updated time stamp included in a beacon message from another sensor. The sensors nodes are supplied by two AA batteries with a normal capacity of 2950 mAh. After 15 days the voltage dropped from 3 Volt to 2.845 Volt. During the subsequent 5 days of testing the voltage dropped almost linear with 0.029 Volt per day. A critical voltage of 2.4 Volt below which the humidity sensor will become unstable, will only be reached after 3 months.

Decision algorithm for processing of the measurement data can be either implemented on the gateway or directly on the sensor nodes. As alternate hardware solution we tested the Preon32 sensor nodes from Virtenio (Virtenio, 2013), providing a virtual machine to execute Java code. The availability of such high programming languages simplifies the programming of algorithms and makes it possible to update the sensor node software for different products loaded to the container.

2.3 Data Interpretation Tools

We want to get a 3D model for the development of temperature with time, even if there are only a few measurement points available. The first example is the estimation of the temperature development of a banana box. Depending on the way of packaging the convective flow of cooling air at a specific box may vary in a wide range (Ambaw 2013). The temperature of the box at loading may vary, too. This way, some boxes cool down within 2 days, others need a week (Jedermann, 2011), which has a major impact on shelf life, of course. We developed a model to predict full cooling curve from data generated within the first 2 days (Palafox, 2011). Figure 3 shows the development of temperature for two example boxes A and B. The temperature has been measured for 3 days. From that, the development for the next 15 days is predicted. This prediction correlates well with the further development of measured temperature. This allows us a more precise estimation of remaining shelf life at an early stage.

Bananas are a climacteric ‘living’ product with biological processes continuing after harvest (Turner 1997). A certain amount of heat is generated by this respiration activity. When the bananas come close to a state, in which ripening starts and the colour changes from green to yellow, the heat production increases simultaneously. If the heat production is larger than the amount of heat removed by cooling, a hot spot develops leading to even higher biological activity and temperature. If a hot spot develops in one pallet, in most cases the whole container is lost.

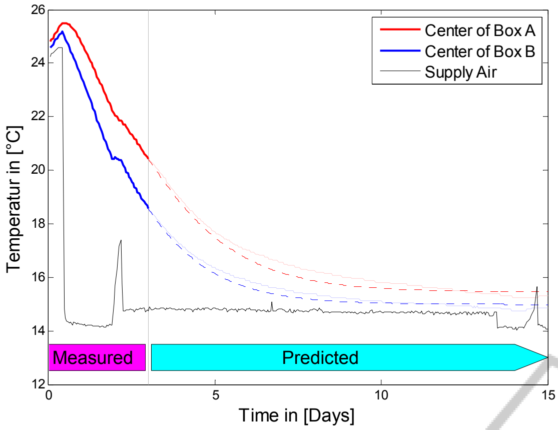

Figure 3: Measurement of the temperature development in two boxes within the same container during sea transport.

The conditions leading to a hot spot can by analysed by an extended version of the model (Jedermann, 2013). Figure 4 shows the measured and predicted temperature curves for an ashore experiment simulating a cooling problem. The set point of the cooling system was switched from 13°C to up to 16°C for 30 hours. For one box of banana (lower curves) the temperature rises, but then declines again as it should. The second box (lower curve) has insufficient cooling air circulation. Biological activity starts, and the cooling system cannot bring down temperature any more. A hot spot is developing. The lower cooling effect was caused by deliberately making a "packing mistake" by completely blocking the air gaps between the pallets.

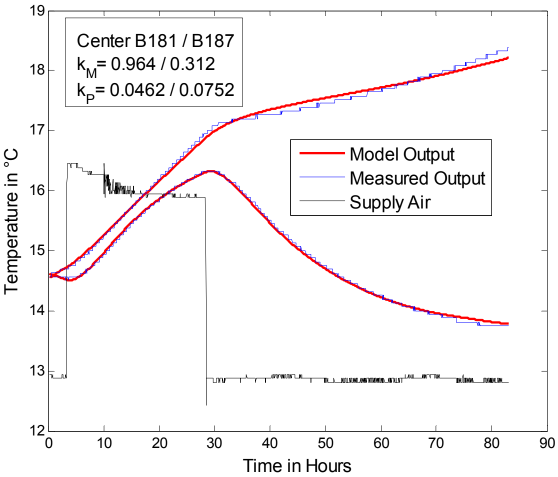

Figure 4: Measurement of the temperature development in two boxes within the same container during sea transport. The model parameter k_P describes biological activity, k_M describes the cooling (Jedermann, 2013).

Different pacing schemas were evaluated and compared by this model (Jedermann, 2013). We found that it is important to carefully maintain slots of identical width for the flow of the cold air. Blocking of convective flow can seriously inhibit the cooling.

2.4 Decision Support Tools

The most important decision support tool of the Intelligent Container is the shelf life predictor.

Figure 5 shows the shelf life curve for lettuce (Tijskens, 1996) using an Arrhenius kinetic approach. The set point is 6°C, so at 6°C the loss is 1 day per day. At higher temperature the loss rises, storing the lettuce at 14°C for 1 day will result in a loss of 3 days in shelf life.

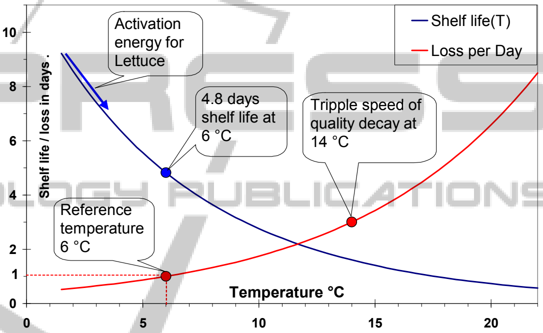

Figure 5: Shelf life estimation: The remaining shelf life is plotted versus temperature for the example of lettuce (Tijskens, 1996). At the set point of 6°C the loss is 1 Day per day. At higher temperature the loss increases and thus the expected shelf life is reduced.

The figure gives only a very simplified idea of a shelf life predictor. Actually, there are complicated biological models behind it which must be elaborated experimentally for every fruit. In order to implement shelf life prediction in an algorithm there are two approaches: the first one supposes reaction kinetics of the Arrhenius type for the fruit. Reaction kinetic parameters are experimentally elaborated for the specific fruit. The decision support tool continuously calculates the Arrhenius kinetics. The second approach uses table shifting. Look up tables for the specific fruit are calculated once and stored.

Today, shelf life predictors are implemented in sensor nodes. Implementation in smart cards comparable to RFID data loggers is on its way (Jedermann, 2008), (Zweig, 2008).

2.5 Field Tests

The sensor system including gateway and external communication were installed in a prototype intelligent container. Three test transports from

Costa Rica to Europe were carried out in 2012 and 2013. After 2 weeks of sea transportation the bananas were left in the container for ripening after gassing with ethylene. The container ripening took 5 or 6 days but showed only a good result with a similar degree of ripeness in all boxes at the end of the process, if several measures to improve the air flow though the boxes were applied (Jedermann, 2013),

In parallel to the sea transportation tests, a further test was carried out for the automated supervision of meat during a truck transport from France to Germany (Dittmer, 2013).

Figure 6: Pallets in test container with antennas for wireless sensors under the roof.

3 ETHYLENE MEASUREMENT

3.1 The Role of Ethylene in Fruit Ripening

Ethylene is a gaseous ripening hormone for most fruits. When fruits ripen, they emit ethylene gas. On the other hand, when a fruit is exposed to ethylene, ripening is induced. This is why ripening is contaminous: put a green tomato besides a red one and it will start induced ripening. Concerning ripening, fruits are classified as climacteric or non-climacteric. Non-climacteric fruits such as grapes and apricots are harvested when fully ripened, they do not show ripening any more after being picked. Climacteric fruits such as bananas, apples or tomatoes have an extended pre-mature phase (green banana) followed by a sudden rise of ethylene emission and respiration. When the climacteric event starts, it cannot be stopped. Bananas are transported in the pre-climacteric state as green banana. After unloading they are exposed to ethylene in a ripening chamber.

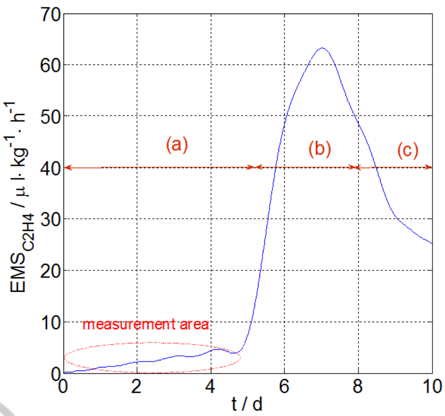

Figure 7: The emission of ethylene by climacteric fruits (banana). To monitor the small rise in the preclimacteric phase (a) a measurement method with very high resolution is needed. (Bials, 1954).

Figure 7 shows the ethylene production. Pre-climacteric (a) the emission is small. The container air will contain ethylene in the range some 100 ppbv (parts per billion by volume). In the climacterium (b) the emission rises strongly and the bananas turn yellow. After the climacterium (c) the emission reduces again and the bananas start decaying. During transport the fruit should stay in the pre-climacteric state (a), but sometimes, if a package is not cooled effectively, ripening may start locally. Ripening bananas emit ethylene and this way trigger other bananas to start ripening, furthermore ripening bananas generate heat and temperature is further increased. These nonlinear effect cause a “hot spot” of ripening. To detect this dangerous effect, the ethylene must be measured with a resolution of 50 ppbv.

3.2 Measurement of Ethylene in Very Low Concentration

At this low level of concentration we find many organic gases in the container, therefore the measurement must be sensitive and selective at the same time. There are gas sensors for ethylene which can measure in the ppmv range, but they do not show high selectivity. For this reason, within the Intelligent Container project we have developed measurement systems for ethylene which are sensitive and selective at the same time.

The first approach is non-dispersive infrared spectroscopy (NDIR). Ethylene shows a specific IR-absorption line at 10.5 µm wavelength. The NDIR measurement provides very robust detection in the lower ppmv range (Sklorz, 2012). For the ppbv range, a more powerful method has to be applied: gas chromatography (GC).

Figure 8: Using the technology of microfluidics, a small GC-column is made for the µCG (Sklorz, 2012).

A gas chromatograph uses the fact, that the adsorption and desorption of the gas molecules at a surface is specific for different molecules. The gas diffuses through a long tube, the chromatographic column. This is filled with a material which has been developed for specific adsorption of ethylene, the stationary phase. By ad- and desorption the molecules are retained, and if a mixture of molecules enters the column at a certain time, each species will reach the end of the column after a specific retention time. The species are detected at the end of a column with a commercial gas sensor. The gas sensor provides sensitivity, the chromatographic column provides selectivity.

Gas chromatographic systems are large and expensive. For the use in transport systems, we developed a small system which can work autonomously.

The column of the µCG is made using micromachining technology as shown in figure 8 (Sklorz, 2013). Using these devices, a resolution of 140 ppmv is achieved. To boost the resolution down to the ppbv range, a micromachined preconcentrator has been developed. This is a micro reactor as shown in figure 9.

The reactor is filled with an adsorption material which can catch and hold the ethylene. The first step of measurement is the accumulation of ethylene in this adsorption material.

When enough gas is assembled, then the reactor is heated up fast and the ethylene is set free in a short boost which enters the CG system. This way, for the first time a resolution below 400 ppbv was detected [Janßen, 2013]. Figure 10 shows a chromatogram of a probe gas of 400 ppbv of ethylene in air. The biggest problem concerning cross sensitivity is water. In the first attempt, the water peak was overlapping the ethylene peak. A new stationary phase (Carbosieve SII) shows different retention times for water and ethylene. This way, it is possible to separate these two species as shown in figure 10.

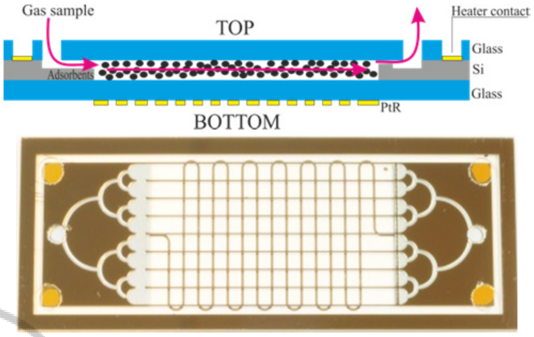

Figure 9: A micro reactor used as preconcentrator for ethylene measurement. By using micro-preconentrators, a resolution in the ppbv-range can be achieved. (Janßen, 2013).

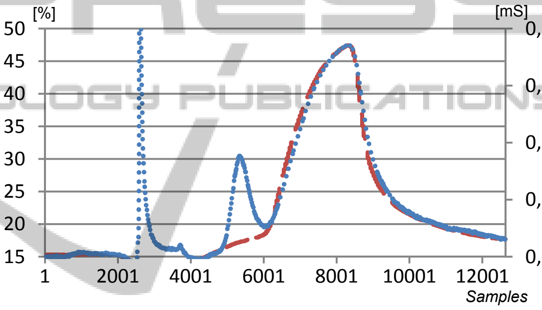

Figure 10: Chromatogram of ethylene (blue line) in air made by the combination of a micro-preconcentrator and a micro-gas-chromatograph [Janßen, 2013]. The red curve shows air with the same humidity but no ethylene content. The ethylene is clearly detected around sample 5200 (1300 seconds). The proof gas has a concentration of 400 ppbv ethylene. The needed resolution of 50 ppbv is provided by this system.

4 CONCLUSIONS

In this paper we described the results of several projects concerning the application of wireless sensor nets in fruit logistics. As a conclusion of this experience we would like to sum up the basic findings about sensor networks within the following theses:

- Loss of fruit during storage and transport can be considerably reduced using wireless sensor networks combined with data interpretation tools and decision support tools.
- The tools must be implemented locally. This means, that they have to be programmed on the small platform of a sensor node and that they must

be implemented parallel on several nodes. Central calculation needs too much energy for the communication of all the the single data and it makes the net too vulnerable.

- Practically, robustness of the system is the main issue. Sensor nodes can fail, they also can just vanish by being forgotten or stolen. For this reason, parallel and redundant structures are needed.
- The housing of the sensor nodes must stand humid surrounding and also mechanic stress such as mechanic impact by pressure and shock.
- There is no off the shelf solution for sensor nodes. Specific surrounding needs specific housings concerning humidity, temperature and mechanic stress. Specific deployments also need specific communication strategies to be able to communicate in difficult situations such as close iron walls and loading with water content.
- Medium term, sensor nodes have to be powered by batteries. Energy harvesting only works if area and light are always available and solar cells can be applied. The energy need of sensors and electronics is declining fast, but the amount of energy which can be scavenged is still too small for most sensor net deployments.

How will the project go on? The next steps will be twofold: Some of the industrial partners of the Alliance for Innovation are now performing application development together with Bremen University in order to launch a sensor net for fruit transport as a product. Second, there is more need on specific sensor technology. At the moment, IMSAS is starting a project to detect the growth of mould fungus in containers during transport.

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