Jedermann, R.; Moehrke, A.; Lang, W.: Supervision of banana transport by the intelligent container. In: Kreyenschmidt, J. (ed.): Coolchain-Management, 4th International Workshop. University Bonn, Bonn, 2010, pp. 75-84

Supervision of Banana Transports by the Intelligent Container

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Keywords: Fruit logistics, Telemetric, Wireless Sensor Networks, Temperature mapping

Abstract: *The improvement of the banana supply chain in order to provide better quality and to compensate for biological variance is still a challenging issue. This paper describes the online-monitoring and supervision of spatial deviations by the Intelligent Container, which is a crucial pre-requisite to improve the transport conditions. Spatial temperature deviations data were collected during sea-transportation of two containers and analysed with regard to differences over the container length, effects of power interruptions, differences between two containers of same type and year of manufacture and deviations inside one cardboard box. Furthermore, the accuracy of a simple setup with only 4 sensors was compared with a setup with 16 sensors distributed over 4 pallets.*

1. The banana challenge

When banana fruit ripening is triggered, enzyme activity accelerates the conversion of starch to sugar generating up to 800 Watt of heat per ton [Ker04]. Beyond a certain point of ripening of fruit, few modes of cool transport can maintain optimum carrying conditions with out damage to sensitive fruit. By understanding the evolution of biological variance from field to store and being able to monitor in time-spatial representative indicators of fruit ripening during transport or storage, a practical model for managing quality needs to be developed. Key outcome of this innovation is to find reliable indicators that allow decisions to be made along the supply chain that can reduce the chance of waste and improved customer satisfaction. Integrated online monitoring of the environment in the immediate surrounding of the fruit should aim to sense and predict the changes in fruit ripening connected to the internal dynamics of a transport unit of fruit.

The greatest risk in banana supply chain is the loss of fruit due to untimely ripening as a result of post harvest decay or fruit physiological factors. Ripening triggers in the field, the packing plant, during transport to the port, and refrigeration in the ship/container. Uncontrolled biological processes during the ripening in Europe or during the final stages of distribution to the consumer also increase this risk. These triggers may take the form of stress to the plant or fruit, variations between hot and cool temperatures in critical periods of time, or mechanical/pathogen damage to the fruit. Awareness and key actions based on reliable/representative indicators can significantly reduce the losses; this results in an energy efficient supply chain as well as meeting quality expectation of the customer/consumer. Since Tropical banana production is a continuous process all year round, identification of problems as soon as possible in the chain can improve the reaction time to avoid repeating the same mistakes.

Although this research project is not finished yet, the presented system and experimental results should help to decide whether ripening and delivering high quality bananas consistently is possible inside a container en route to the market by giving a better understanding of the related processes.

1.1. Online monitoring

So far, the temperature tests have been mainly carried out with data loggers. Temperature data can be read out only offline at the end of transport. The data loggers have to be either electrically connected or placed in close proximity in line-of-sight to the reader. But the challenge above to improve the banana supply chain can only be met by an online monitoring system, which provides permanent access to quality and temperature data in order to take corrective actions during transportation when mechanical access to the sensors inside the container is not possible. This paper focuses on the test of such an online monitoring system as a precondition to improve banana sea-transportation processes.

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1.2. The idea of the intelligent container

The concept of the intelligent container was proposed in 2006 [Jed06] in order to meet these challenges. It augments standard telemetric solutions by a sensor network for online access and intelligent processing. The temperature of each pallet is either directly measured or interpolated by an adequate number of sensor points. In general, the intelligent container locally pre-processes the sensor data and sends only the warning messages if a threat of quality loss is detected. But in contrast to the shelf life modelling presented in 2006, this paper focuses on the results from the first field test of the technical system. In the future, the intelligent container will also apply gas sensors for the detection of unwanted ripening in an early stage. A high resolution ethylene sensor will be presented in a separate contribution in this conference.

2. Test setting

The first pilot test of the communication system for the intelligent container was carried out in September 2009. The required components were installed in two refrigerated containers. Both containers were equipped with a Carrier Transicold Thinline cooling unit (year of manufacture 1997). The two containers loaded with bananas were shipped from Costa Rica to Hamburg. Temperature records from a previous offline test with data loggers in 2008 were also included in the evaluation in section 3.

2.1. Sensor nodes

A wireless sensor network forms the core of the system. Twenty sensors nodes were distributed per container. The sensor nodes are based on the TmoteSky/TelosB platform [Mot06], which provides a short range radio to transmit temperature and humidity data. The radio operates in the 2.4 GHz range with a transmission power of 1 mW. The sensors are powered by 2 AA-size batteries. The measurement data are sent to a gateway.

If a direct communication is not possible, the data are forwarded over multiple hops. The ZigBee [Zig07] standard could not be used because of its disadvantages for multi-hop sensor networks. Sensors, which are programmed to forward data from other sensors, cannot be put into sleep mode in between messages. In order to prolong the battery life a new network protocol was programmed, which is directly based on the underlying 802.15.4 standard. A Paper with a detailed description of the said network protocol is in preparation.

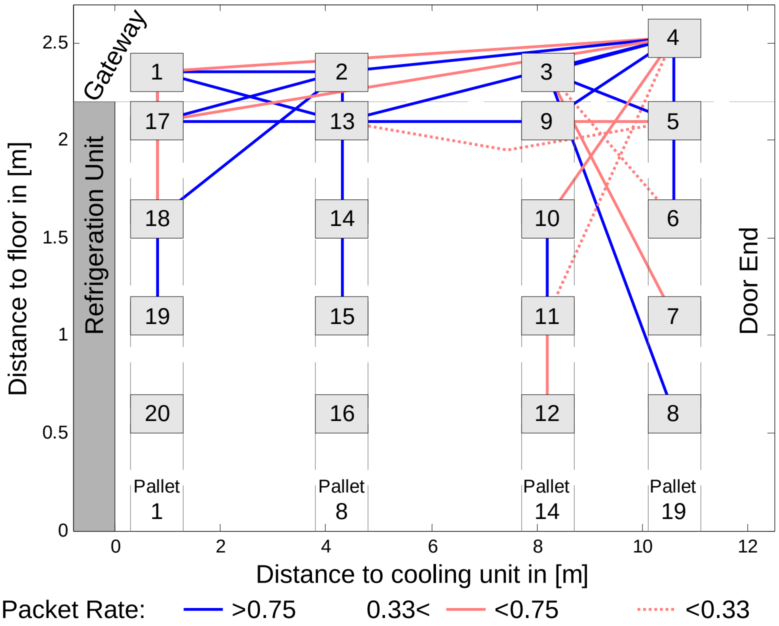

Fig 1: Sensor positions and radio links inside container

Figure 1 gives an overview of the sensor positions. Four pallets were equipped with 4 sensors, each in different tiers (number 5-20). Four additional sensors were placed on top of the pallets in order to forward data, if the direct links between the pallet sensors are too weak.

2.2. External Communication

The data from the sensor network inside the container has to be forwarded over several units until it is available at the web server of the University of Bremen. A communication gateway, mounted beside the cooling unit, collects the data from the sensor network. The Gateway sends the aggregated data to the captain’s bridge over a standard wireless LAN. From there, the data is fed into the ship's email system. An INMARSAT satellite link forwards the data to our web server. The user can query the data by a standard web browser. The user can access an overview with minimum, maximum and average values of the container; or, a detailed view of current temperature of individual sensors and their history can also be accessed. **Figure 2** summarizes the communication structure. A detailed description is given in [Bec09].

2.3. Communication problems

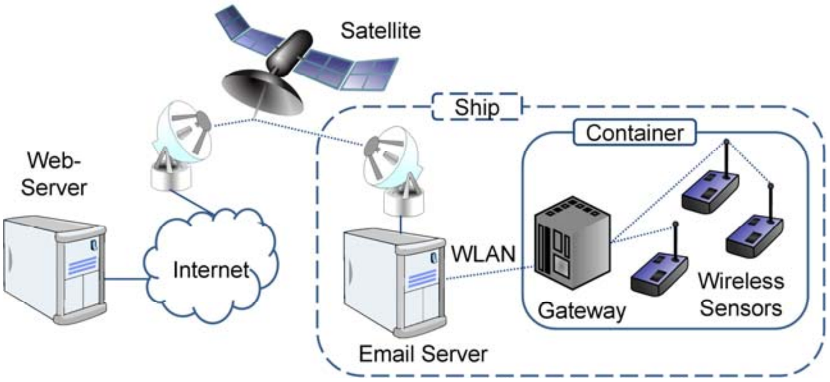

Fig 2: Overview communication infrastructure

Containers are an unfriendly environment to install electronics. The electronics have to withstand mechanical shocks during transhipments as well as high air humidity and condensed water. But, the signal attenuation by the loaded fruits turned out to be the major obstacle for remote monitoring. The water content of the bananas largely affects the transmission of high frequency radio signals inside the container. Even for distances of 0.5 meter, equal to the vertical distance between the sensors, in average 50% of all data messages were lost. One-third of all links with a distance of 0.5 meter failed completely, another third had temporary dropouts, and the remaining third provided stable communication. The lines in Figure 1 indicate the packet rate of all usable radio links in one of the two containers. Some of the missing links were compensated by the network, for example the gap between sensors 9 and 10 was bypassed by a link over sensor 4 outside the pallets. But two sensors in each container remained completely disconnected from the network and were not available for online supervision. The temperature data were recovered from the flash memory of the sensors after end of the experiment. In order to compensate for the high signal attenuation by water containing food products, it is necessary to switch to another radio platform. The ZigBitAmp radio module from Atmel, formerly Meshnetics [Atm08], provides similar features as the TelosB, but also possesses higher radio transmission power of 100 mW.

3. Observed temperature deviations

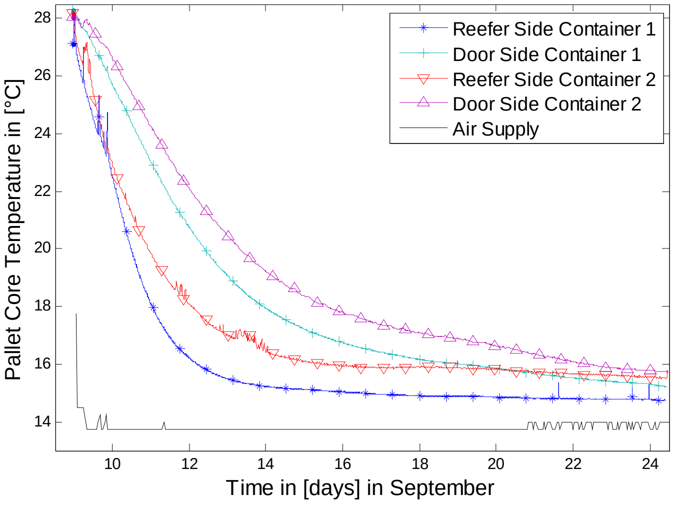

Fig 3: Effects of pallet positions and container to core temperature

As in several other tests [e.g. Tan03], it was found that the temperature clearly depends on the location inside the container and thereby proved the need for spatial supervision. **Figure 3** shows the temperature over time function for the pallet core temperature at both ends of the container for the experiments from 2009. Although the temperature deviations are almost equalized after end of the transport, the speed of the cool-down process showed large variations. The time span that is required to cool down the pallet to 17 °C was compared. The cooling process for pallets close to the refrigeration unit took in average 58% less time than for those at the door-end of the container. Both containers used the same type of Transicold cooling equipment, but a large difference between their temperature behaviour was also revealed. The cooling process in container 1 was in average 39% faster.

The average cooling speed in the experiment in 2008 was similar to container 1 in 2009, with less spatial deviations. The differences between door-end and refrigeration side were only 33%, compared to 58% in 2009. This more even temperature distribution could have been caused by the lower age of the cooling unit (Transicold Thinline, 1999), but also by differences in the packing arrangement.

A lately finished test with a newer container (Thermoking Magnum Scroll, 2008) showed only a little difference between door and aggregate side (11.3%). The cooling process was as fast as in the best measurement in 2009 on the aggregate side. But pallets in the middle of the container required 37.8% more time for cooling down than those at the container ends.

The supervision of product temperature requires measurements directly inside the pallets at different locations in the container. The built-in sensors of the cooling unit for supply and return-air temperature give almost no information about the pallet core temperatures. Differences between return and supply temperature are only an indicator for an ongoing cooling process, but the supply and return air temperature were always lower than the temperature in any pallet in our measurements (**Figure 4**).

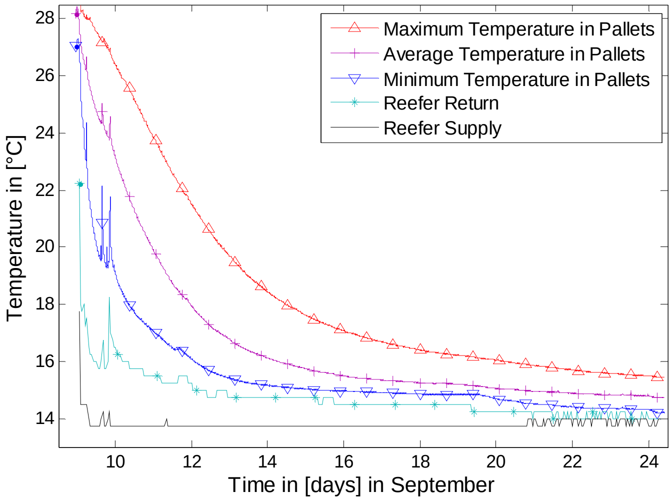

Fig 4: Internal Sensors of refrigeration unit and temperature inside pallets

3.1. *Temperature rise during power disconnection*

The power supply was disconnected for 6 hours for transhipment in the harbour in the 2008 test with an ambient temperature between 28 °C and 32 °C. The temperature of the air above the pallets rose by 6 °C (**Figure 5**), but the effect on the loaded pallets was rather marginal. Their surface temperature increased by 0.2 °C per hour. The pallet core temperature showed only an interruption of the cooling process and remained at a constant value during the period with disconnected power supply.

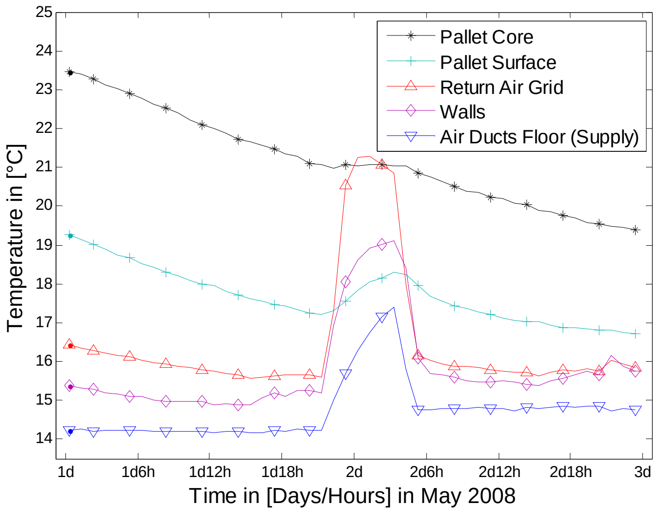

Fig 5: Effects of interruption on power supply to temperature in different positions

3.2. *Effects of different positions inside the box*

Two additional boxes were equipped with 10 data loggers each. The loggers were placed in different positions inside the box, e.g. centre and corners of the box, inside and outside the plastic bag, which prevents humidity losses (**Figure 6**). A comparison of the different positions showed a standard deviation of temperature inside one box of about 0.5 °C, if the box was not in touch with the container walls. It was not possible to detect an influence of the plastic bag on the temperature. Only the temperature in the box centre was 0.5 °C higher than the average of the other positions, but this is only a rough estimation with regard to the standard deviation. If the box is placed close to the container walls, the temperature at the inner side of the cardboard box (Pallet surface in Figure 5) can be several degrees lower than the core temperature.

Fig 6: Wireless sensor nodes (left) and data logger in two additional boxes (right)

The quality depends on the pulp temperature, but the sensors for transport monitoring can only measure the temperature between the bananas inside the box. The resulting error was estimated during an additional experiment. The sensor readings for 26 boxes were compared with the pulp temperature measurements by a needle thermometer. The temperature measured between the bananas was in average 0.05 °C higher than the correct pulp temperature with a standard deviation of 0.08 °C for the static case without air flow.

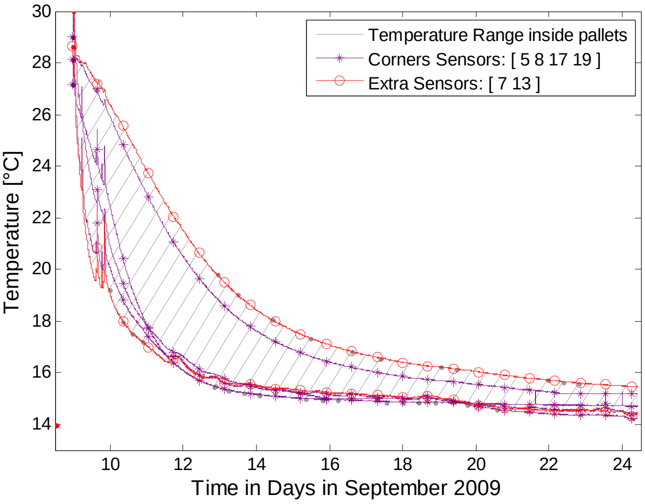

Fig 7: Range of box core temperatures (hatched area), detection of min/max by corner and additional sensors. Sensor numbers in brackets refer to Figure 1.

4. Required sensor density

In order to predict the temperature of individual boxes or pallets, it is necessary to represent the spatial temperature distribution by a model. The simplest model assumes a linear rise of temperature between the side of the refrigeration unit and the door-end. A linear relation between temperature and the vertical position of the box inside a pallet can also be taken into consideration. Only few sensors positions are required to predict the temperature for any point in space with such a simplified model, for example 4 sensors placed in the first and the last pallet, belonging to the lowest and the highest tier. But, it has to be questioned whether such a minimal sensor setup is sufficient to represent the spatial temperature distribution.

It was tested whether 4 corner sensors are sufficient to capture the minimum and the maximum temperatures for any box inside the container. Unfortunately, this approach failed for one of the two containers in 2009. The corner sensors were compared against the remaining 12 sensors inside the pallets. But, two additional sensors are required to cover the full temperature range as shown in **Figure 7**. The hot-spot of the container was found in tier 4 of the pallet close to the door, whereas the coldest box was found in the top tier of pallet 8 in the middle of the container. But, the position of the cold and hot-spots varies between different shipments. So, it is hard to say in advance in which box an additional sensor should be installed.

The linear prediction based on the measurements of 4 corner sensors failed in similar fashion. The prediction was compared with the measurements of the remaining boxes. The average mean square error was lager than 1 °C for one-third of the predicted points.

Four probe points are clearly insufficient to give a reliable representation of the container. We assume that at least the double or triple number of sensors is required. But for a scientific answer to this question, further experiments with a closer grid of sensor points have to be carried out. The influence range of cold- and hot-spots has to be estimated. In order to make sure that at least one sensor is placed in the proximity of each local temperature peak, the distance between sensors has to be smaller than this influence range.

5. Intelligent data processing

The processing of the sensor data is another crucial issue apart from the placement of a sufficient number of sensors. Simply transmitting all measured data would cause tremendous costs if a satellite link is involved. The most obvious step to reduce the communication volume is to preprocess the temperature data by a shelf life model and send only the warnings if a certain threshold is overstepped [Jed06]. The mathematical equations can be calculated by a small microcontroller, and the first commercial product is already on the market [Amb09]. But, unfortunately, there is no model for bananas yet available; simple Arrhenius type models are far from accurately predicting the ripening state of bananas.

The software of the intelligent container is not restricted to analysing the sensor data with regard to quality; it can also investigate dependencies between temperature, time and space. Several more algorithms were tested in simulation experiments. A spatial interpolation by the Kriging method [Jed09] can fill missing temperature data for pallets which are not equipped with a sensor. Alternatively, a modified method can decide which of the sensors can be powered down if their measurements can be replaced by interpolation of their neighbours. Furthermore, the intelligent container can predict the future temperature development based on the measurements of the first 3 or 5 days [Pal10].

6. Summary and outlook

The experiments showed that an online-supervision of sea-transports is feasible, although some technical challenges still have to be met, such as high radio signal attenuation by the fruit. The recorded data showed that the pallet core temperature cannot be estimated by general assumptions without measurements in several spatial positions. Factors such as position, differences between containers and the packing contribute to temperature deviations. The built-in sensors of the refrigeration unit failed completely to predict the banana temperature. The pallet core temperature has to be directly measured by wireless sensors. But a direct relation between pallet temperature and observed quality defects could not detected in our experiments. A model to predict the progress of the ripening process has to include additional factors like gas concentrations and biological variance at harvest time.

The further development of the Intelligent Container will be continued by a new consortium with 3 universities and 13 companies, founded by the German Government (Federal Ministry of Education and Research / BMBF, DLR). Dole Germany OHG, the Leibniz-Institute for agricultural engineering Potsdam, CHS Special Container Shelter and Engineering GmbH, OHB Teledata GmbH and the Institute for Microsensors, -actors and –systems (IMSAS) will contribute their knowledge to finally meet the banana challenge after the 3 years project duration.

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7.1. Acknowledgment

This research was supported by the German Research Foundation (DFG) as part of the Collaborative Research Centre 637 “Autonomous Cooperating Logistic Processes”. We especially thank Dole Europe Import BVBA, Belgium for the support in field tests. Further project information can be found at www.intelligentcontainer.com