4.6. Intelligent containers and sensor networks Approaches to apply autonomous cooperation on systems with limited resources

Reiner Jedermann[1], Christian Behrens[2], Rainer Laur[2], Walter Lang[1]

[1]Institute for Microsensors, -Actuators and -Systems (IMSAS), University of Bremen
[2]Institute for Electromagnetic Theory and Microelectronics (ITEM), University of Bremen

4.6.1. Introduction

RFIDs, sensor networks and low-power microcontrollers are increasingly applied in logistics. They are characterized by restrictions on calculation power, communication range and battery lifetime. In this article we consider how these new technologies can be utilized for autonomous cooperation and how these processes could be realized on systems with limited resources.

Besides tracing of the current freight location by RFID technologies, the monitoring of quality changes that occur during transport is of growing importance. The demand for improved and comprehensive supervision of goods could be best fulfilled by distributed autonomous systems.

The 'intelligent container' as autonomous supervision system

The prototype of our 'intelligent container' demonstrates how autonomous control could be implemented on a credit-card sized processor module for integration into standard containers or transport vehicles (*Figure 1*). The processor provides a platform for local interpretation and pre-processing of sensor information. The system automatically adapts to the specific requirements of the transport good. An extended electronic consignment note that is implemented as software agent contains individual transport- and monitoring instructions. RFID technologies are used to control the transfer of this mobile freight agent. The implementation of the local data pre-processing and an example quality model for vegetables are described in section 2. If the supervision system predicts that the freight quality will drop below an acceptance threshold before arrival, it contacts the transport manager. The extended agent platform for further transport planning is shortly introduced in section 3.

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

Autonomous control of wireless sensor networks

Incorrect packing or poor isolation could lead to local temperature maxima or ‘hot spots’. Because of the number of required sensors a wireless solution is the most suitable way to monitor spatial deviations of environment parameters. Sensors that are attached to the freight have to link themselves ‘ad hoc’ into the communication network of the vehicle. Section 4 gives an overview over the design, configuration and control of our implementation of a wireless sensor network. Standard algorithms for self-configuration already exhibit features of autonomous cooperation. Because service intervals should be prolonged as long as possible and there is no practicable solution for recharging, battery lifetime is more crucial as in other common mobile applications like cell phones. Besides improvements on the hardware and communication protocols we focus on energy saving by intelligent control. The energy consumption mainly depends on the number of measurement and communication cycles. An intelligent decision system could reduce their required number. Section 5 discusses architectures, examples and further demands on autonomous cooperative processes running on low-power microcontrollers. Approaches for future implementations of an autonomous decision system on small battery powered sensor nodes and logistical freight objects are summarized in section 6.

Requirements of improved supervision and control systems

The design of improved transport supervision and control systems has to consider limitations of communication bandwidth as well as requirements for just in time decisions and extended sensor monitoring. Special attention has to be paid to the following aspects:

Mobile communication

Communication is a substantial component for the implementation of networks of distributed autonomous processes. Technologies for secure and cost efficient communication have to be provided. During system design, the bandwidths of the communication links have to be considered. To save costs for mobile services, the transferred data volume should be reduced by shifting interpretation and decision processes to the physical origin of the data as close as possible. The effects of moving the scope of communication from the transmission of sensor raw data towards the transfer of conclusions and decision rules are handled in detail by Markus Becker.

Extended sensor monitoring

For a detailed sensor monitoring, it is not sufficient to distinguish between ‘intact’ and ‘damaged’ goods. Quality losses depend on the duration and amount of deviations from the optimal transport conditions. Spatial variations of environmental parameters have to be assigned to the affected packages. A concise prediction of quality changes assumes complex data and decision guidelines.

Robustness

Transport monitoring systems have to work in rough environments. Communication links might not be available or some of the involved systems could be damaged. Sensor measurements might be faulty. Solutions for supervision and control systems should be robust enough to continue their work despite system failures in their neighbourhood.

Just in time decisions

Corrections to the supply chain should be carried out as fast as possible, at least before the next part of the production chain is entered. A permanent supervision is necessary to avoid a freight reaching its destination with insufficient quality. Decisions should be made synchronously to the time-span that is required by the related real-world processes. This is, for example, the time that is left before the last turning point for a changed route is passed, or the time needed by the thermal mass of the freight to warm up if the reefer aggregate fails. The decision process assumes that the related information could be transferred from the sensing to the execution unit (actuator) without violating timing restrictions. Additional communication links should be avoided to minimize the risk of delayed decisions due to communication failure.

Networking of embedded systems

The communication budget of each sensor node is very limited due to its battery capacity. For this reason central data collection and evaluation has to be replaced by local processing and data compression. It should be considered whether decision processes could be divided into smaller units and distributed among a network of low-cost microcontrollers. The idea of networking embedded measurement systems is comparable to the approach of ubiquitous computing, that was originally meant to embed miniaturized processors into everyday objects (Mattern 2005).

Application in food logistics

The logistics of food and especially agricultural products is an outstanding example for dynamic demands that are placed on transport planning. Planning has to take into account that market and order position are subject of permanent alterations. Although road transport from Spain to North Europe is about tree days, large customers like retailer chains expect their orders to be fulfilled within 20 hours (Dannenberg 2006). Changing weather conditions affect both sides of the supply chain. If the conditions are too bad for harvest, the purchaser has to fall back to an alternative cultivation area. The consumer behaviour is weather dependent, as well. Certain fruits like melons are not very well sold during rainy periods.

Transport planning has to take in account that product quality can fall below an acceptance limit which leaves the transport without shelf life during retail and thus without economic value. To avoid economic losses supervision of food quality during transport can be applied. The evaluation of the huge amount of data that is produced by detailed supervision assumes concise knowledge of the product.

Supervision devices can de divided into data loggers and telemetric remote monitoring systems. In many cases, several incompatible technologies are used within a single transport. Data loggers are packed together with the freight, the reefer aggregate records temperature and humidity values; the temperature is manually read once per day on sea transports. Sensor protocols are mainly used to settle liability questions after damage has occurred.

Telemetric systems are on their way into food logistics. In contrast to data loggers, they enable early corrections in the transport planning. The System of Cargobull Telematics[1] sends periodically data about position (GPS) temperature, tire pressure and state of the reefer aggregate. Doors are only to be opened in predefined allowed areas. Otherwise an alarm is sent over mobile communication, for which GPRS is currently used. IBM and Maersk announced a similar module called TREC that can be mounted to the door of a container. It measures temperature, altitude and light and transfers data over satellite communication[2]. Standard tariffs for the Cargobull system offer temperature and position information updated every 15 minutes for a monthly rate about 50 Euros. To keep inside an inclusive volume that is negotiated with the network provider, high-level data compression is necessary. The inclusion of additional environmental data

[1] http://www.cargobull.de/en/produkte_und_dienstleistungen/ cargobull_telematics/Produkte/default.jsp

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

and their spatial distribution requires advanced data pre-processing and interpretation to avoid increased communication costs that will not be accepted by transport companies.

4.6.2. Local data pre-processing

Evaluation of quality changes demands not only detailed information about environment parameters but also guidelines on how this data should be interpreted. In this section, we show as an example how deviations from the optimal transport conditions for certain vegetables could be related to quality changes.

Perception systems for intelligent agents

Distributed autonomous control systems are mainly realized by software agents. The perception of the external world is an important feature of intelligent agents according to Bigus (Bigus 2001, p. 235). Agents need an internal representation of their environment for decision-making. An intelligent agent has to avoid to be overwhelmed by the flow of information by filtering or pre-processing the incoming data. The perception system of a fully automated transport planning can be divided in two parts. In the 'inside' of the means of transport, dynamic parameters like the number and kind of loaded goods, as well as the temperature and other environmental conditions have to be supervised and interpreted. On the 'outside', permanent changes in transport orders, cost and the effects of the traffic situation to the expected transport time have to be considered.

Automated interpretation of environmental data in food logistics

The inspection of food quality is, in practise, carried out by visual inspection of only a small part of the total freight. Most of the more scientific ways like measurement of firmness or starch content require opening of the package and destruction of the fruit. Furthermore, although visual inspection or chemical tests provide information about the current quality, they cannot predict future quality changes as function of the transport conditions over time. For real-time transport control quality changes have to be assessed based on parameters that are suitable for continuous monitoring. These are environmental condition like temperature, humidity and the composition of the atmosphere.

In the recent years there has been a lot of research in the modelling of quality (Tijskens 2004). As example for various modelling approaches we consider the keeping quality model. Tijskens and Polderdijk (Tijskens and Polderdijk 1996) found that the time-span that is available for transport and storage before the quality falls below an acceptance threshold depends of the inverse sum of a number of temperature dependent coefficients. These coefficients can be calculated as a function of the environmental temperature by the law of Arrhenius with the reaction specific activation energy as parameter. Parameter sets for 60 different agricultural products are listed (p 178). *Figure 2* shows the maximum transport and storage time for tomatoes as example. The product lifetime is reduced by senescence (mostly during high temperature transport) and chilling injury (low temperature transport). To account for changing temperature conditions during transport the model was formulated in a dynamical form (p. 182).

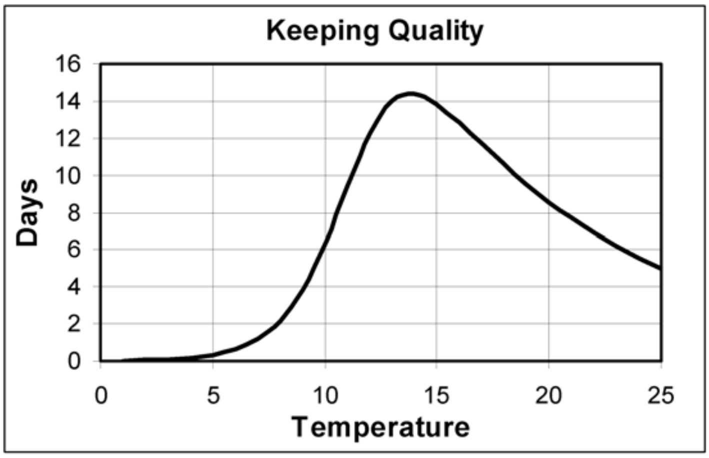

Fig. 2. Keeping Quality for tomatoes according to Tijskens. Temperature dependency of the maximum time-span for transport and storage before the product quality falls below an acceptance limit

To make these models more accurate, they have to be extended to include the initial quality at harvest, which depends on the climate conditions and other influence factors. Especially the gaseous hormone ethylene has an important impact on the ripening of a number of agricultural products. Additional research is necessary to determine the quantitative effects of ethylene as well as for the development of miniaturized cost effective sensors for mobile measurement of ethylene concentrations.

Implementation of a local perception system

To increase the robustness of the system and to reduce the communication volume, assessment of the environmental conditions were implemented as local processes. The means of transport is equipped with a processor module that provides a platform for the perception system. In our technical implementation we shifted the product specific perception processes and the necessary technical investments from the transport packing to the level of the transport vehicles or warehouses for practical reasons: Transport packing rarely returns to the sender. Expensive sensor or processor equipment would be lost after the end of transport. The means of transport has to be furnished with RFID readers to scan for new freight items, sensors for supervision of the transport conditions, external communication and a processor platform. Our prototype in *Figure 1* shows an example implementation of the required hardware. The technical system is described in (Jedermann et al. 2006b).

During transport the freight items enters the dominion of local supervision systems that represent the involved transport vehicles and warehouses. By separation of the perception processes from the physical object the mobility of freight specific instructions becomes another crucial feature of the system. In our solution the perception was realized as mobile software agent. The software and the object are linked by address information stored on a passive RFID-Tag that is attached to the freight. The agent accompanies the physical object along the supply chain as part of an extended electronic consignment note containing the transport and supervision instructions. At transhipment the address of the system that currently holds the consignment note is read from the RFID-Tag. With this information the transfer of the mobile agent through the communication network is initiated. The local supervision systems form an intelligent infrastructure that provides for sensors and processing power to the loaded freight items (*Figure 3*).

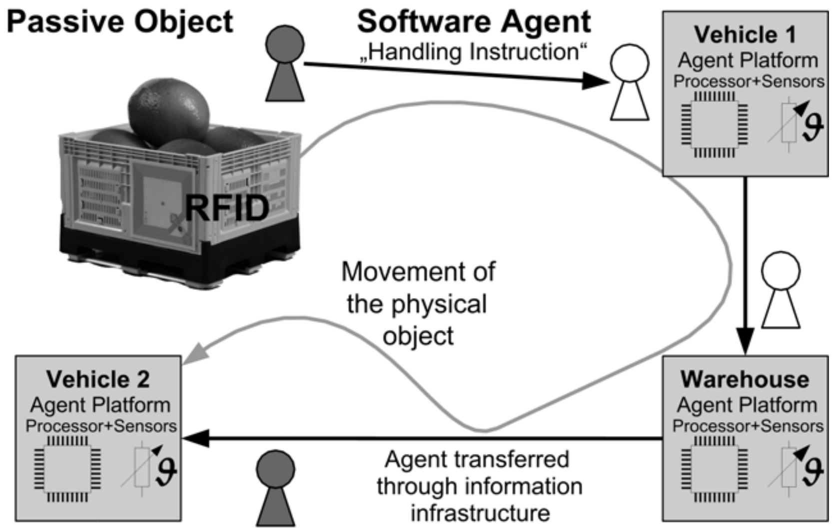

Fig.3. The link between physical object and mobile perception system. The freight is handled by different vehicles and warehouses along the supply chain. Arriving items are recognized by an RFID reader. A mobile software agent that contains the individual perception systems is transferred in parallel to the freight object. Required sensor systems and processing power are provided by the local platforms

As first step towards the goal of distributing autonomous processes to miniaturized systems, we examined facilities to run software agents on embedded processors with a computational power comparable to handheld PDAs. We selected an ARM-XScale processor module that provides about 10% of the clock rate and memory of a standard PC. The reduced processor architecture additionally slows down the code execution. Measurements by Jedermann (Jedermann 2006a) showed that the execution of agent systems takes 50 to 100 times longer than on a PC. That article also describes necessary optimizations in the agent framework. A special real-time JAVA virtual machine was required to run JAVA as basis of the framework on the embedded processor.

An implementation of the keeping quality model was worked out in cooperation with Horticultural Production Chains, Wageningen University (Jedermann et al. 2006c). The quality model is executed as software agent on the local system. If it predicts that quality will drop below an acceptance limit before the destination could be reached, the agent contacts the route and transport planning instances to initiate necessary reactions. The external communication is carried out by a unit developed by ComNets, University Bremen that switches between different mobile networks (e.g. WLAN, GPRS or UMTS) depending on availability.

Relation to the definition of autonomous cooperation

The local perception system depicts the essential features of autonomous cooperation according to the definition that was described in chapter 1.

The interpretation of the sensor measurements is organized as a **decentralized concept**. An individual software entity represents each specific transport good; the perception agents are executed close to the current location of the physical object by a distributed network of processor platforms. Each means of transport has own sensor and processor resources at his disposal.

Transhipments are carried out among partners that are on the same **heterarchical** system level without a central operator. Data are transferred peer to peer between vehicles and warehouses. Different communication standards can be used side by side.

The concept of the intelligent container allows for fully **autonomous** supervision, even if external communication links or remote processor platforms fail. The system reacts to unexpected events like sensor failures, temperature rise by sunlight or defects of the reefer aggregate without interference from humans or other systems.

The intelligent container **interacts** with other systems to retrieve freight specific information and the consignment note. The perception system negotiates with the sensors how to distribute the measurement task, which is performed in **cooperation** of several sensor nodes.

To improve the cooperation with the sensor network and the transport planning the autonomous transport supervision system has to go beyond calculation of quality models. Especially situations that allow for **alternative** reactions have to be considered. The **decision** system is still under development. It will be extended to fully cover the following topics:

- **Distribution of the measurement task**: A number of the available sensors are selected according to their tolerance, location and remaining battery lifetime.
- **Plausibility checking**: The system decides whether unusual single sensor values should be handled as measurement error or as an indicator for a spatial or time limited deviation of the environment.
- **Quality assessment:** The perception process decides whether a current deviation of the transport condition leads to an unacceptable quality losses.
- **Reactive planning**: The transport planning selects between different options to react to foreseeable quality losses.
- **Energy reduction**: Intelligent sensors could minimize their energy consumption by reducing the number of measurement and communication cycles. Section 5 discusses the feasibility for equipping miniaturized sensor units with a decision system.

The consequences of these decisions depend on future events like changes in communication quality and network topology and unknown external influences to the environmental conditions. The system behaviour could also depend on internal states that are unknown or not measurable like the harvest conditions of the product for example. The decision-making has therefore to be regarded as **non-deterministic** process with no clear right/wrong decisions. The possible consequences of several possible reactions have to be weighed up instead.

4.6.3. Linking quality information and transport planning

Decision processes of the transport planning system are based on two sources: quality information and external factors like traffic situation and the market of available transport capacities. Transport decisions are made in cooperation of different agents. A freight attendant (FA) acts from the point of view of a single transport item and coordinates its complete transport. The FA negotiates with different agents, which represent a means of transport (MTA). The MTA endeavours to maximize the use of their capacities. The acceptance of a transport orders by the MTA depends on the transport costs, destination and time schedule. The transport request is compared against the sensor equipment and reefer capacities of the vehicle.

Demonstration system for dynamic transport planning

The ‘intelligent container’ and the agent based transport planning developed by the TZI (Centre for Computing Technologies, University Bremen) were linked to a common demonstrator. FA and MTA verify regularly whether the requirements of the freight could be fulfilled. If a risk is detected the FA searches for alternative plans that could possibly include a change of the means of transport. In this case the FA and MTA start to negotiate about changing the destination of the vehicle.

The freight and vehicle administration agents currently have to run on a standard notebook as separate software platform. The perception agents on the embedded system and the PC based planning agents use both the JADE framework (Bellifemine et al. 2003). The FA and MTA are not tied to a particular location. An optimization of their consumption of processing power and memory would allow executing them on the same embedded platform inside the means of transport as the perception agents. The plans for future development will at least shift the FA to the embedded system. The software approach of the demonstration system is described in (Jedermann et al. 2006d).

Examples for dynamic planning

The described system shows its most advantages if the shelf life and the transport duration have a comparable magnitude, which is the case for most fresh fruits as well as fresh meat and fish. Because of their distinctive ripening behaviour bananas are excellent examples for the use of quality information for dynamic planning. Bananas are harvested in an unripe 'green' state. After their two or three weeks ship transport they are exposed to ethylene in special ripening rooms for up to one week. During this forced ripening process starch is converted to sugar and the colour changes to yellow. The aim of warehouse keeping is to have an even mix of different ripening states in stock. This process can be improved by a system that permanently monitors the ripening state and sends notifications about quality changes one or two weeks ahead of the planned arrival of the vessel. The further distribution of the fruits also demands careful planning. Weekly deliveries to retailers are partly composed of bananas in three different ripening states. This allows them to offer bananas in perfect condition on a daily basis.

Another example might be the road transport of strawberries from south to north Europe. Bad weather conditions at harvest could cause severe quality problems. If the content of some trucks is lost, the remaining vehicles could be redirected to share the remaining undamaged freight evenly among the costumers and fulfil all delivery commitments at least partly.

4.6.4. Measurement of spatial distributed environmental parameters

Deviations of the environmental conditions could affect the means of transport as a whole or only a spatial limited share of the freight. To detect the latter case a multi-point measurement is required. If the difference from the prescribed transport condition rises, it could result in a local quality loss. The detection of these local quality losses is a crucial issue, because already the decay of smaller parts of the freight could endanger the whole transport. To identify such risks in good time it is necessary to distribute sensors over the entire length of the container. The use of wireless sensor networks for data transmission could reduce additional installation costs.

Examples for local parameter deviations

Especially the temperature in reefer containers is subject to severe fluctuations. Measurements with several data loggers showed differences of 5°C over the length of a container (Tanner and Amos 2003; Punt and Huysamer 2005). These or even greater deviations are caused by bad thermal isolation or wrong packing that blocks or short cuts the air stream of the reefer aggregate. Reefer containers and vehicles are not designed to cool down food from harvest conditions to transport temperature. European regulations like the HACCP[3] concept demand that only pre-cooled goods are loaded. But violations of the rule happen not only outside Europe. Absorbing the heat of 'warm' goods could take more than a day with large difference between air and freight core temperature as a side effect.

The formation of local 'ripening spots' has to be avoided. This effect is mainly observed at see transports of tropical fruits. The intensified metabolism processes lead to a further temperature rise. For this reason the transport of fruits at a temperature between 10 °C and 15 °C requires more energy for cooling than deep frozen goods. Besides the temperature rise the fruits start to produce ethylene themselves, which stimulates

[3] Hazard Analysis and Critical Control Points (HACCP) is a systematic preventative approach to food safety that addresses physical, chemical and biological hazards as a means of prevention rather than finished product inspection.

ripening processes in neighbouring fruits. This effect could in the end lead to a total loss of the transport. To estimate the effects of local losses onto the behaviour of the whole freight requires further modelling.

Key features of wireless sensor networks

Wireless sensor networks (WSN) consist of tiny-networked embedded devices, which act as the network nodes. These nodes are formed by a microcontroller, a RF-Interface and sensors and are usually powered using batteries. While designing such systems, usually COTS (Commercial Off-The-Shelf) components are used in order to reduce system prices. The consequences of this concept will be shown later.

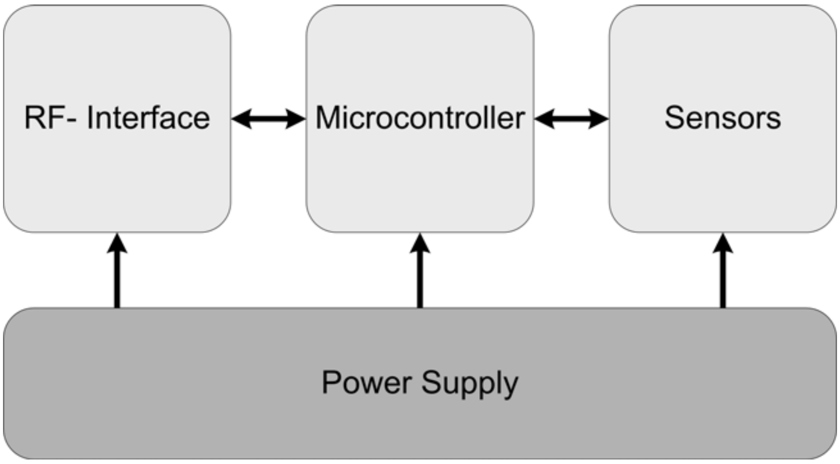

Fig.4. Wireless sensor node architecture

In the past five years, a lot of research projects on various aspects of WSN have made extensive advances in this field possible. The major aspects were system design (Handziski et al. 2005), communication protocol design (Woo and Culler 2001) and how to interact with a WSN (Madden et al. 2003). Some of these research projects brought forth advanced concepts and systems, which are paving the way to WSN applications in industry.

The concept of WSN offers a lot of benefits for the integration of intelligent sensor systems into logistic supply chains. These benefits are wireless ad hoc communication, security and robustness.

- **Wireless Ad Hoc Communication:** All nodes in the networked are linked wirelessly. This gives the opportunity of monitoring the transported assets continuously. If any disturbance is detected, the WSN system may inform autonomous cooperating units, which will evaluate the disturbance and may trigger necessary reactions. No extra effort has to be made for the integration of the additional sensor nodes into the WSN. The systems may either be fitted to the freight items or may be deployed before or after the loading process. After being turned on and detected by the network within the transport medium the nodes autonomously log into the network. As an RF interface an IEEE802.15.4-compliant transceiver was chosen, which is used by many other WSN platforms (IEEE 2003).
- Privacy and Security are important aspects for the integration of WSN into autonomous cooperating logistic processes. The data of the systems may neither be readable to unauthorized parties nor be tampered in order to inflict damage to the system. In order to provide this, advanced security provisions and cryptography are integrated as shown in (Benenson and Freiling 2005; Gorecki 2006) to the WSN system.
- **Redundancy and Robustness**: Another important concept of WSN is redundancy. If a node fails (e.g. due to empty batteries, failure of subsystems), its role is simply taken over another node in the network. The application of COTS components is simply a consequence of redundancy. This feature also enables

correlation of sensor readings in the network and application plausibility checks. This also increases the robustness of the overall system.

Within the CRC 637 several WSN platforms have been evaluated and a new platform has been developed that is based on the widely used Telos B platform by Moteiv[4]. In contrast to Telos B, our WSN prototype system, offers a modular sensor interface. This enables eased usage of several different sensor types with the proposed platform.

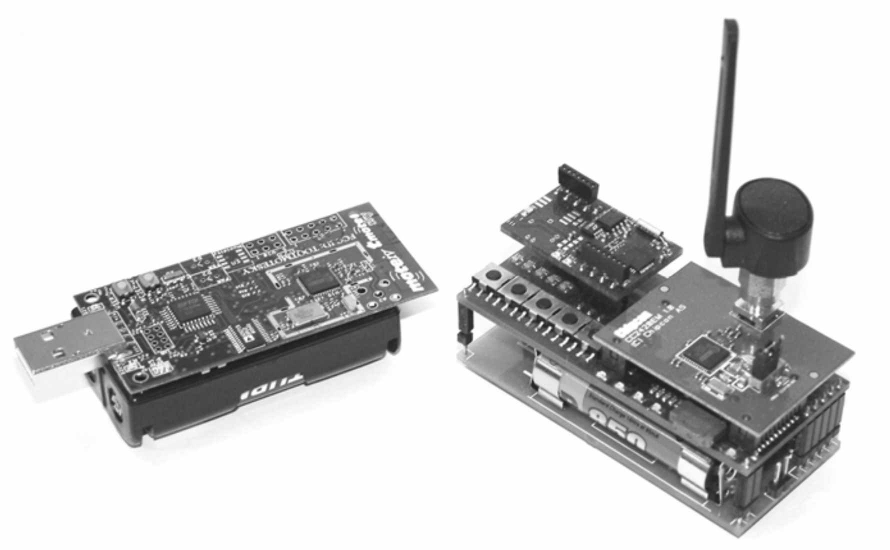

Fig. 5. Commercial Moteiv system (left) and SFB637 WSN system (right)

The above description shows that wireless sensor network constitute a promising technology for the integration of sensors in supply chain management.

4.6.5. Applying autonomous cooperation in sensor networks

The previous sections described how the concept of autonomous cooperation was implemented to improve the supervision of quality parameters at the level of transport containers or vehicles. The following chapter will discuss to what extent this concept could be adapted for the coordination of the sensor systems inside the container and whether it is possible to reduce classical agent system architecture for these resource-constrained devices.

The self-configuration of sensor networks can already be regarded as an autonomous cooperating process. Rogers (Rogers et al. 2005) gives an example how the message forwarding is organized by local control. The autonomous approach should be extended to other systems tasks. Especially the question when and how often energy-consuming measurements and communication procedures have to be triggered demands an intelligent selection among different alternatives.

As previously described, the hardware that is used at the transport system layer has approximately 10% processing resources of conventional PCs. Compared to this the computational power of the microcontrollers applied in wireless sensor nodes is even a hundred times less. Unfortunately the calculation power of low-energy microcontrollers increases not as fast as Moore's Law[5] let assume.

[4] www.moteiv.com

[5] From recent developments Moore's Law extrapolates that the complexity of integrated circuits doubles every 18 month. But this mainly applies to PC components where the huge market volume allows for large technical investments.

Standard architectures for distributed agent systems were developed on conventional PC based systems without restriction to computational power or communication. It has to be questioned whether and to what extend these approaches could be adapted to resource-constrained systems and if the restrictions in performance of the individual elements can be equalised by increasing their number.

The well-known approach of Grid computing enables solving highly complex problems by collaboratively employing unused computing resources of hundreds to thousands of PCs. As given by Walter (Walter 2005), problems that employ the processing of several independent data streams can be solved by microcontroller clusters by application of tools and methods from Grid computing. Especially problems that require a high number of interrupt-triggered tasks can be solved more efficiently by using several coupled embedded systems then by employing single high-performance CPUs. The grid computing approach may not be applied directly for the distribution of autonomous cooperating processes within a network, as Grid computing is based on centralized control and hierarchical structures.

Approaches for reduced hardware

Solutions have to be found for the distribution of tasks in a network of computationally small systems. Some of the approaches that have been applied to this question like swarm intelligence, fuzzy and agent architectures are introduced in the following sections.

Swarm intelligence

The intelligence of swarms observed in nature is often quoted as example solution. Ants search the shortest path by following a pheromone track left by their predecessors (Bonabeau et al. 1999). A swarm of fishes agrees on a swimming direction without requiring a communication intensive voting. By coordination with their imminent neighbours the individuals balance contradictory information about the best direction and avoid break-up of the swarm (Pöppe 2005). The intelligence of the swarm cannot be concluded from an isolated view on the behaviour of a single individual. It is not even necessary that each individual knows the super ordinate aim of the swarm.

Deliberative and reactive agents

Wooldridge and Jennings (Wooldridge and Jennings 1995, p. 24) describe deliberative architectures as the classical or symbolic AI methodology for building agents. A deliberative agent is characterized by

- an explicitly represented symbolic model of the world and
- decision making via logical or at least pseudo-logical reasoning

Unsolved problems in applying the deliberative approach on time-constrained systems have led to the development of reactive architectures. Wooldridge and Jennings (Wooldridge and Jennings 1995 p. 27) define „*a reactive architecture to be one that does not include any kind of central symbolic world model, and does not use complex symbolic reasoning*“.

Especially the ‘subsumption architecture’ from Brooks 1986 has gained much attention. Different vertically layered behaviour patterns are continuously computed in parallel. From this ‘behaviour set’ a single behaviour is chosen to dominate the reaction of the system. The higher layer patterns decide whether they superimpose the lower layers. Brooks employed this approach for the control of robots. For example if a module is activated that cares for returning to the power station for recharging the batteries all lower layers will be blocked. The behaviours for exploration of the surroundings and keeping a minimum distance to obstacles are no longer executed.

Using this layered approach increases the overall robustness of the system. If a single layer fails the whole system keeps its capacity of acting. The essential difference to conventional systems is that the robot does not employ a view of its world. No symbolic world model needs to be developed, as the reactions depend only on current observations of the environment. The robot responds to changes in its surrounding in a form that corresponds to reflexes. This approach may be also combined with a symbolic representation of the world, E.g. the robot generates a map in order to reach distant destinations (Bergmann 1998). Using this extremely simple architecture concerning its computational complexity Brooks achieved astounding results:

But despite this simplicity, Brooks has demonstrated the robots doing tasks that would be impressive if they were accomplished by symbolic AI systems. (Wooldridge and Jennings 1995, p. 28)

Learning

The ability to learn from previous actions is seen as another prerequisite for intelligence. Due to the limited lifetime of a freight object the opportunities for application of learning processes for transport supervision are restricted. The individual quality dynamics are very variable and may not be translated to other freight classes. Already at the beginning of a transport this knowledge has to be completely present. A learning process is only viable on a meta-layer by incrementally building a knowledge base concerning specifics of certain freight classes. Furthermore it is possible that the internal wireless communication network incrementally adapts to communication disturbances caused by the spatial distribution of the freight items within the transport medium.

Examples of intelligent sensor systems

The application of agent-oriented architectures for the control of embedded systems and sensor networks has already been researched in the past. Two examples from literature are summarized in the following section.

Target tracking by radar sensors

One approach to control and coordinate a distributed sensor network was presented by the group of Lesser (Lesser et al. 2003; Mailler 2005). They describe a sensor network for discovering and tracking moving targets. Each sensor node has three independent radar sensors that cover an angle of 120°. In their research they selected a setting that forces local processing and cooperation:

- At least 3 sensor nodes have to cooperate for triangulation.
- The node has to decide in which direction it looks for new targets, because only one of the three radar sensors can be activated at the same time.
- A very limited communication bandwidth prevents central data interpretation and sensor control.
- All sensor data have to be processed in real-time before distance measurements become obsolete.

To reduce communication the sensors are organized in clusters. Best results were achieved with fixed clusters of 5 to 10 sensors (Mailler 2005, p. 11). Architectures for dynamic coalitions forming were also considered (Lesser et al. 2003, pp. 110f). A dynamic coalition is formed in response to an event like the detection of a new target and dissolved when the event no longer exists.

Each sensor is represented by an agent that can take on different roles. One agent in each sector acts as the sector manager that disseminates a schedule to each sensor with frequencies to scan for new targets. When a new target is detected, the sector manager selects a track manager that is responsible for tracking the target as it moves through the environment. The track manger requests and coordinates other sensors and fuses the data they produce (Mailler 2005, p. 6).

The target tracking utilizes the same JADE framework to execute the agents as our transport planning system. But it moves the agent platform to an external computer. The radar nodes are only equipped with a simple processor to control the communication unit and the hardware of the sensor elements.

Fuzzy agent architecture

Human operators are often better at control of complex and non-linear technical processes. Zadeh (1965) who introduced the theory of “fuzzy sets” proposed that the reason for the human superiority is that they are able to make effective decisions on the basis of imprecise linguistic information. Fuzzy logic has become an increasingly popular approach to convert qualitative linguistic descriptions into non-linear mathematical functions. *Fuzzy rules provide an attractive means for mapping sensor data to appropriate control actions* (Hagras et al. 1999 p. 324). Hagras et al. combine Brooks subsumption architecture with fuzzy logic controllers (FLC). Each layer or behaviour of the subsumption architecture is represented by one FLC. An additional FLC is used to combine the output of the different layers. The parameterization of the FLCs is performed by a patented genetic learning mechanism. This hierarchical fuzzy agent was tested for the control of robots. In another implementation the fuzzy learning technique is used to adapt an "intelligent dormitory" that is located at the University of Essex to the personal preferences of a guest (Hagras et al. 2002). The fuzzy agents run on a Motorola 68030 processor with a computation power that is about ten times lower than those of the embedded platform for the intelligent container.

Self-configuration as autonomous cooperative process

Wireless sensor networks are a perfect indicative of autonomous cooperation. As an example the network formation process is discussed with a focus on autonomous cooperation.

The most intuitive way to network WSN devices is to use a fully-meshed network topology. This means that all the nodes in the network are interconnected. This network topology is the optimal representation of heterarchy, as any node in the network may communicate with any other node at once as shown in *Figure 6*. However, in wireless sensor networks there are restrictions regarding communication in the network.

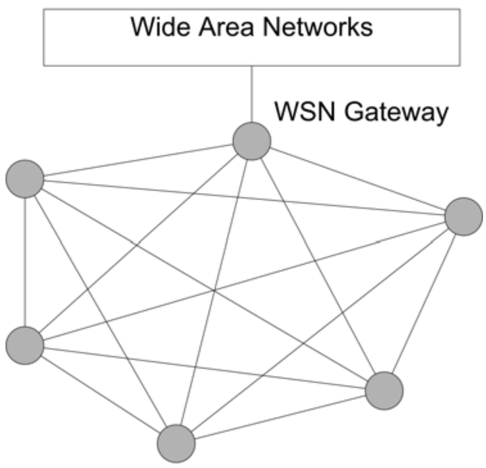

Fig. 6. Fully-meshed network topology

A very important aspect that comes into play when designing WSN systems is energy consumption. This is mainly due to dependence on batteries. When taking a closer look at the energy consumption of the three parts (microcontroller, RF-transceiver and sensors) as shown in *Table 1* it is clear to see that in common WSN systems, the RF-transceiver consumes around 20 to 40 times the energy of the microcontroller. The energy consumption of sensors should not be neglected, but is highly dependable on the application and is not taken into consideration here. Therefore, communication among the nodes in the WSN has to be kept as minimal as possible in order to enable longer system lifetimes. However, this is a contradiction towards the paradigm of autonomous cooperation. Therefore, pure heterarchy has to be traded-of against energy-efficiency.

Table 1. Power consumption of selected WSN platforms

	Telos B	Mica2[6]	MicaZ	iMote2[7]
CPU sleep, Radio off[8]	0.0153 mW	0.054 mW	0.054 mW	0.1 mW
CPU on, Radio off	5.4 mW	36 mW	36 mW	>100mW
CPU on, Radio Tx/Rx	58.5 mW	117 mW	75 mW	>150mW
CPU on, Sensors active[9]	7.2 mW	37.8 mW	37.8 mW	>100mW

The power consumption of the WSN platform that was developed within CRC637 almost matches the power consumption of the Telos B platform.

Taking these necessary limitations for WSN systems into consideration, another type of topology has to be found. One possibility is to use hierarchical concepts like clustering. The basic idea of clustering is that a group of network nodes form a cluster (*Figure 7*). One device is elected as cluster head of this cluster for a certain period of time. The cluster head manages the communication with any other device that addresses a node inside the cluster, so it acts as a gateway to the cluster. Using this method, the workload is distributed among the network nodes and communication and energy consumption are reduced.

Thus, network lifetime can be prolonged by a factor of up to 4 (Younis and Fahmy 2005), while this cluster-based-topology also allows very simple collection and aggregation of the data.

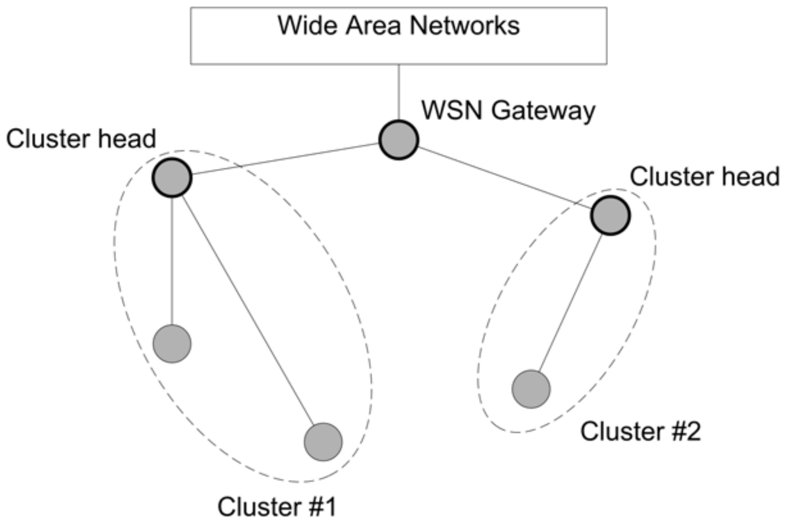

Fig. 7. Cluster-based network topology

After expiration of the cluster head period all devices start to compete for the next election. If a node that is currently cluster head fails, the election process will be restarted among the remaining nodes. If new nodes enter the network during a cluster head period they will enter as a cluster member. Different clusters are identified by an address supplement. This ensures the formation of multiple clusters. The size of the clusters varies with the number of nodes in the network and of the corresponding RF power settings of the nodes. For

[6] Both Mica2 and MicaZ were developed by Crossbow Inc. For more information refer to www.xbow.com

[7] The iMote2 platform has been developed by Intel. Compared to the other platforms in the table it features a PDA-class CPU which has more computing power, but also incorporates increased power consumption.

[8] CPU is in sleep mode while the RF unit is switched off. This is usually valid for more than 99% of the operation time of a sensor node.

[9] Here values for a commonly used humidity/temperature sensor (Sensirion SHT15, www.sensirion.com) are shown.

very large numbers of nodes even multi-tier hierarchical clustering is possible in order to ease the network management.

The cluster head election process is mainly probability-based while the random value is influenced by factors like the number of packets sent and received, number of sensor readings, total time running and how often the device had been elected cluster head before. WSNs provide a mapping of heterarchy in order to prolong system lifetime. All nodes in the network participate autonomously in the topology formation process. Therefore, this process is collaborative and decentrally organized. Various aspects of autonomous decision are also included in WSN systems. E.g. the nodes may autonomously decide on routing of messages, if their energy level falls below a certain threshold.

The knowledge of sensor about the "world" is mainly represented by tables containing information about the known neighbouring sensors and values for the quality of corresponding communication links.

All these features show that the topology formation process is one example of autonomous cooperation in wireless sensor networks. Other examples of autonomous cooperation in wireless sensor networks are e.g. routing of messages, data aggregation, and cross-network correlation of data.

After consideration of the above aspects WSN systems imply several aspects that can be seen as autonomous cooperating process.

The scope of an extended decision system

An appropriate distribution of the measurement task could lead to large reductions of the power consumption of the sensor nodes. But available solutions fall behind the crafted configuration of the sensor network. Standard software packages merely check thresholds or calculate mean values. The energy consumption mainly depends on the number of communication and measurement cycles. An intelligent distribution and control could prolong battery lifetime by omitting redundant cycles.

Decision alternatives

To minimize the effort for communication and measurements the system has to choose between different possible alternative actions. The scope of the decision system covers the following fields:

- **Distribution of the measurement task**: The supervision task has to be distributed among the sensor nodes with regard to their tolerances, resolution and individual power consumption per measurement. The battery reserves should also be taken into consideration.
- **Forwarding of measurements:** If a sensor node observes a deviation of a value the node has to weigh up whether it should spend energy to transfer the value to the transport planning. Before an expensive multi hop communication to a central system is initiated the node contacts his immediate neighbours. Cooperative decisions include measurements of several nodes to avoid duplicate or unnecessary notifications. Crucial deviations have to be distinguished from measurement noise.
- **Requests for additional measurements:** For conspicuous sensor values the node could request additional measurements from its neighbours for confirmation. The costs per measurement vary by a factor of more than thousand for different environmental parameters. Semiconductor temperature sensors spend 0.1 mJ (0.0001 Joule) per cycle. While gas sensors require heating to 200°C or 300°C of the device with an energy consumption of more than 100 mJ. The frequency of such measurements should be reduced as much as possible. Measurements of other 'cheaper' sensors could be an indication for the decision whether the activation of a high-energy sensor is necessary.
- **Plausibility checking:** Plausibility checking is not directly linked with energy. But the distinction between measurement errors and spatial confined or time limited deviation of the surrounding conditions is very important for the robustness of the system. The decision could be based on comparisons with other nodes or on a record of former local measurements.

Boundary conditions and demands on the decision system

Decisions have to be made from a local point of view because the communication costs increase with the distance or the number of network hops. In a cluster topology decisions are made in cooperation through agreement or local voting. The choice between different possible reactions requires complex decision processes. The results of the possible alternatives are often uncertain. Some influence factors are unknown or cannot be measured with sufficient exactness. Because of the non-deterministic system behaviour the alternatives cannot be reduced to a wrong / right decision. Advantages and risks of the alternatives have to be compared instead.

The aim of autonomous cooperation is to quickly find a stable solution where a concise calculation of the optimal solution is not adequate. The decision processes of the sensor system have to be designed for robustness against failure of other systems or breakdown of communication links. Sudden changes in the environment or faulty information should not lead to instability of the overall system.

The power consumption of the processor that controls the sensor nodes is almost proportional to the computational load. Merely averaging of measurement values requires much less energy than communication. Different decision algorithms have to be selected by their power consumption. New simplified solutions for miniaturized microcontrollers have to be developed. The power consumption of the decision system has to be lower than the amount of energy that is saved by selection of a better reaction alternative. The required computation power per decision (Joule per decision) has to be compared against the consumption of measurement and communication cycles (Joule per cycle).

Intelligent freight objects

The developments towards autonomous cooperation, which were presented at the example of sensor networks, could be considered as signpost for further research. In future implementations the freight items could be equipped with miniaturized microcontrollers and ultra-low-power sensors. They connect themselves to neighbour items to extend their communication and measurement facilities. The “intelligent package” makes decisions about its transport route, negotiates with different vehicles for transport and detects quality risks on its own.

Another aim is to support these items over an electro-magnetic field comparable to passive RFID tags. But unlike pure identification tags, batteries are still required to make the system capable of measurement and planning even in the absence of a field. The “VarioSens” data loggers from KSW-Microtec[10] are an example of such a semi-passive system. The temperature logging is powered by a paper-thin battery, but the energy that is required for communication is provided by the electro-magnetic field of the reader.

4.6.6. Summary and outlook

To design a concise supervision for transports of perishable goods several requirements have to be taken into account like efficiency of mobile communication, measurement and assessment of spatial distributed sensor data, stability of the solution in case sub-system or communication failure, just in time capabilities as well as the implementation on embedded systems and their networking. In this article we presented autonomous cooperation as a robust solution to handle the vast amount of spatial scattered sensor data.

Wireless sensor networks and RFIDs are supporting technologies to supply the necessary information to autonomous processes. Furthermore, the wireless sensor networks feature ad hoc networking capabilities while providing sufficient means of communication security and robustness.

[10] KSW-Microtec AG, Dresden, Germany http://www.ksw-microtec.de

The agent framework JADE was implemented on a high-performance embedded processor to provide a platform for local pre-processing that reduces the communication volume and avoids overheads caused by central planning.

The system features like permanent access to the freight state, instant notifications on quality problems and the option for automated route planning provide important advantages for the huge application field in food logistics. The keeping quality model was introduced as method to evaluate sensor data.

The application of autonomous cooperation at the level of the sensor nodes may also be increased beyond the implementation of self-configuration mechanisms. To extend the sensor node's battery lifetime by reduction of communication it is necessary to move the decision-making ability into the sensor network. Decisions have to be made from a local instead of a bird's eye view. The translation of this approach into application requires further research. Expectable increases in the performance of microcontrollers promote these developments. But the anticipated growing of calculation power at same or lower level of energy consumption reaches not far enough to replace the development of algorithms that are specially adapted to low-power microcontrollers. An agent framework like JADE is probably not feasible on low-cost sensor nodes. The solution would rather be a combination of reactive behaviours and logical reasoning. The organisation of the nodes in clusters is expected to deliver the best results.

The fitness of a solution is finally judged by its energy balance. The energy that is necessary to calculate a decision has to be less than the saved costs for measurement and communication.

Information technologies are of growing importance for transport planning and supervision. Autonomous cooperation will be one of the key concepts in systems that go beyond nowadays remote temperature monitoring.

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