

# MICA: A Mobile Support System for Warehouse Workers

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## ABSTRACT

*Thousands of small and medium-sized companies world-wide have non-automated warehouses. Picking orders are manually processed by blue-collar workers; however, this process is highly error-prone. There are various kinds of picking errors that can occur, which cause immense costs and aggravate customers. Even experienced workers are not immune to this problem. In turn, this puts a high pressure on the warehouse personnel. In this paper, the authors present a mobile assistance system for warehouse workers that realize the new Interaction-by-Doing principle. MICA unobtrusively navigates the worker through the warehouse and effectively prevents picking errors using RFID. In a pilot project at a medium-sized enterprise the authors evaluate the usability, efficiency, and sales potential of MICA. Findings show that MICA effectively reduces picking times and error rates. Consequentially, job training periods are shortened, while at the same time pressure put on the individual worker is reduced. This leads to lower costs for warehouse operators and an increased customer satisfaction.*

*Keywords: Assistance System, Interaction-by-Doing, Positioning, RFID, Warehouse*

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## INTRODUCTION

The four fundamental processes of a warehouse are (Tompkins & Smith, 1998):

1. To receive incoming goods for storing,
2. To store goods until they are required,
3. To prepare requested goods for shipping (picking), and
4. To ship the picked goods (sometimes called packing).

Among all the processes of logistics, picking is the most problematic one because it is highly error-prone (Miller, 2004). Many different types of errors are known (Lolling, 2003): picking of wrong types or quantities of articles, complete omission of a type, and insufficient quality of delivered articles (see Figure 2). All these errors cause high costs for manufacturers and warehouse operators. Either because extra shipments and returns are necessary, or, in the worst case, because contract penalties have to be paid.

In today's lean production, where only small resource reserves are kept at the manufacturing site, the resources necessary for production are usually delivered to a customer just when he needs them. The orders are possibly known to the warehouse weeks before but delivery is expected exactly at the specified date. If an important item from the order is missing, this can mean that the whole production has to stop, incurring extra costs for the warehouse for courier delivery, and the customer who then lets the warehouse pay for the financial damage of the production halt. Besides causing huge costs, this certainly has potential to annoy customers. Accordingly, the primary goal for warehouses is to eliminate or at least reduce the number of errors.

Especially warehouses with human workers are confronted with returns caused by incorrect delivery of items. But although humans constitute the soft spot in this process, completely automated solutions are not an option for most warehouses because human workers are much more flexible (see Figure 1).

During economic peak times, warehouses are forced to employ unskilled workers in order to cope with the increased workload. These unexperienced workers are not familiar with the structure and organization of the warehouse,

yet have to be operational in a short time. They do not have the time to learn from experienced workers where an ordered article can be found, what the fastest routes through the warehouse are, what the exact processes are, or what a certain article looks like.

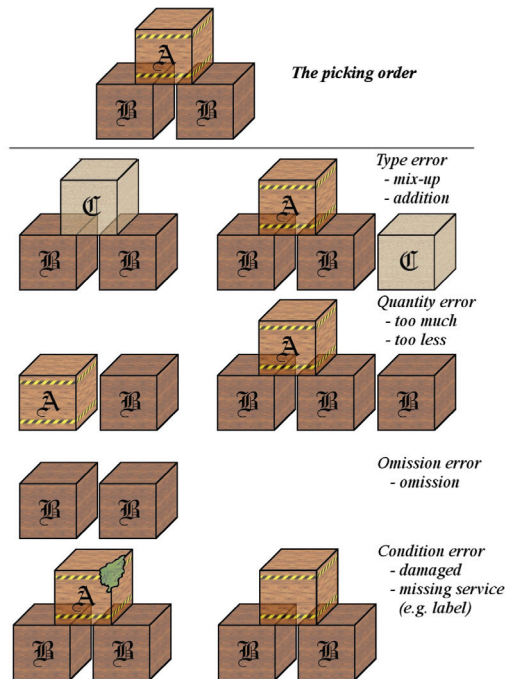
Nevertheless, work has to be completed without errors and under the same high time pressure that also skilled workers face. Picking errors and time pressure constitute the major problems for unskilled and skilled workers. Hence, there is a need for an intelligent assistance system that supports the workers. By preventing errors, such system also reduces the pressure put on each single warehouse worker. An assistance system for employees needs to support untrained workers as well as experienced workers in their usual way of working and not force them to change habits.

Based on an initial requirement analysis, we propose the Interaction-by-Doing paradigm, which was realized in a first MICA prototype. Its success led to the development of the second MICA pilot for field testing in a productive environment. In a field test we evaluated MICA's usability, its effect on worker efficiency and estimated its world-wide sales potential. Finally, we present related work and conclude.

*Figure 1. Worker in a non-automated warehouse*



Figure 2. Picking errors



## REQUIREMENTS AND CONCEPTS

In collaboration with two medium-sized non-automated warehouses, we initially collected requirements for our envisioned MICA system. Such system would reduce the pressure put on workers by assisting them with their tasks, and by preventing errors and the costly effects thereof.

For end-users and designers, design proposals can be understood as design probes to explore the characteristics and usefulness of a proposed system. When a prototype is available, end-users can try it and gain personal experience with it. The active involvement of users and a clear understanding of their tasks is the key for a successful system development.

The ISO 13407 “Human-centred design processes for interactive systems” standard does not prescribe specific methods for how to achieve these goals; they are to be chosen according to what is state of the art and what

is appropriate under the respective project circumstances. Based on practical experiences from other projects, we have devised a scenario-based approach, combined with user interviews, participatory observation and expert analysis, based on the structure proposed by Robertson and Robertson (1999) for mastering requirements.

Their Volere process ensures that all important aspects of requirements are carefully addressed and that the methods applied have proven their value in practical work. The Volere process makes a distinction between global constraints affecting the project, functional requirements and non-functional requirements. Associated with this process is the Volere template. The template makes fine-grained distinctions between different types of requirements and requires that they are assessed in various categorizations. It also captures the rationale for each requirement as well as fit criteria. These criteria are used to evaluate customer satisfaction and dissatisfaction if a require-

ment is implemented or not. Hence, the Volere process ensures that all important aspects of requirements are carefully addressed.

## REQUIREMENTS

The requirements gathering process was directed by interviews with all stakeholders and focus groups at the two involved warehouses. These provided valuable insight into the work at the warehouse and contributed to a worthwhile understanding of the current and immanent problems, limits, tasks and benefits of a future support system. But much more important than the interviews and focus groups was the participative observation of the work in the warehouses for several days. Initially, the warehouse workers were quite cautious to work exactly to rule but soon they completely forgot the presence of the observers and reverted to their old habits.

Quite remarkably this brought to light several important issues that would never have been discovered with interviews or focus groups: we could observe workers that were deliberately committing errors. For example, when an item was missing or broken they scanned in the correct bar code from the shelf and put another (wrong) item into the order box, thus producing two severe errors: an order with a wrong item (mix-up error) and removing another item from the warehouse that would leave the warehouse inventory in an inconsistent state, causing a missing article in a subsequent order.

The reason for this observed behavior was the cumbersome process that had to be followed when an item of an order was missing or broken: the warehouse worker had to stop his picking and take the warehouse manager in. First he needed to find the warehouse manager in his office – usually on the other side of the warehouse – then inform him that an item was broken or missing. This could lead to some awkward situations due to the short-tempered nature of the warehouse manager. After that both had to go back to the location in the warehouse,

so that the warehouse manager could investigate the situation. Then, mostly not without anew critique, the warehouse manager had to go back to his office, enter the error into the system and restart the picking order. Only now the worker could continue picking. This easily could consume more than 30 minutes.

All in all we collected over 50 requirements that were prioritized by our own observation and by experienced workers and warehouse managers. The most important requirements can be summarized as follows:

- (i.) Reduce error-rates. To be effective, MICA must reduce error-rates compared to existing assistance systems. Only this alleviates the workers' fear of picking errors, while at the same time justifying the use of MICA from an economic point of view.
  - (ii.) Provide the opportunity to process several picking orders at the same time. As experienced workers tend to process several orders at the same time to reduce walking distance.
  - (iii.) Support trained and untrained workers. MICA must support trained as well as untrained workers, because at peak times the permanent staff is reinforced with unskilled workers. Both groups have inherently different needs. Unskilled workers need a certain time to acquire the knowledge where to find an article. Navigation assistance should help to avoid making detours and to find articles on the picking list. At the same time, MICA should not interfere with habits of experienced workers.
  - (iv.) Unobtrusive guidance. A novel technology gets rejected if people have to change their way of working or if they feel patronized. To achieve acceptance, a guidance system may not require much attention but should work in the background. It should only draw attention to prevent a picking error.
  - (v.) Usability. Interfaces should be intuitive, provide a good overview and be easy to
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learn because user training is expensive. Keeping the system responsive enables seamless user interaction and avoids idle time for workers.

- (vi.) Working hands-free. Simultaneous handling of mouse or keyboard would disrupt picking. Additionally, workers are usually unfamiliar with computer user interfaces.
- (vii.) Environmental conditions. Different environmental conditions play an important role for MICA. For example, the display should remain readable under unfavorable light conditions, while sound should remain hearable despite ambient noise.

## INTERACTION-BY-DOING

From above requirements, we derive MICA's Interaction-by-Doing concept that builds on multi-modal and implicit interaction with a calm computing system that provides pro-active help to users with different experience levels. The different concepts' implications are described in the sections below. Interaction-by-Doing is an enhancement of Interaction-by-Movement (Lorenz, Zimmermann, & Eisenhauer, 2005). Interaction-by-Movement means that moving towards a location is recognized by the system, which reacts with a proactive help. In Interaction-by-Doing, interaction is not reduced to movement only but to multiple kinds of behavior. By this, no explicit interaction is necessary.

A practical example is the picking process: when picking with support of a scanner, the worker passes articles by his scanner. The scanner confirms with an acoustical response. Not till then may the worker continue picking. In contrast, when the process is extended with an Interaction-by-Doing system, the worker just puts an article into the box. The Interaction-by-Doing system identifies the article in the background and interrupts the worker (using an appropriate modality) only in case of an error. Interaction-by-Doing eliminates the additional control process in picking and automatically

helps with solving the problem by telling the user to remove the wrong article.

## MULTI-MODALITY

People's interaction in a completely engineered environment relies on different modalities because a single modality may fail in a certain situation. For example, people in motion cannot focus their full attention on the interaction with a touch screen (Brewster, 2002). In contrast, noisy environments make speech less reasonable than other modalities.

## IMPLICIT INTERACTION

In explicit forms of interaction the user assertively communicates his wishes to the system via specific IT devices like mouse, keyboard or touch screen, and well-known interaction rules like clicking, dragging or typing. Other explicit interaction forms like gesture recognition can be socially obtrusive if they involve sweeping gestures. When such gestures are required for interaction, the user might feel embarrassed because it looks strange to casual bystanders. Still, even if more subtle gestures (like a small tilting) are used, the user wants to explicitly and consciously communicate something to the machine.

Implicit interaction is a passive form of formulating wishes. The idea is to analyze natural movement of the user and to derive reactions by the system. To be able to extract interaction information the system needs to know the tasks and intentions of the user in the specific context. Implicit interactions are unobtrusive but are also less reliable.

Yet the success of a system is highly dependent on its usability because simple and intuitive interaction increases user acceptance. Natural interaction means multi-modal interaction with explicit and implicit interaction modalities. Therefore, the idea of MICA is to offer a suitable interaction modality to every particular situation.

## **CALM COMPUTING**

Weiser and Brown came up with the term of calm computing. They demanded that technology engages both the center and the periphery of our attention, and in fact moves back and forth between the two (Weiser & Brown, 1997). In MICA, the normal picking process remains the center of the worker's attention. MICA stays in the periphery where additional information about the current task can be retrieved. It only moves to the center if an error occurs. A system based on the Interaction-by-Doing principle beholds the workers' actions with various sensors to detect problems.

## **PROACTIVE HELP**

Proactive applications want to give adequate help when the user is expected to need it (Kaufmann et al., 2007). A computer system offers proactive help if it deems that this could reduce a worker's stress or if he is about to make an error.

The intention is not to point out that the worker errs but to avoid errors. This saves time and reduces worker frustration. Because of that, help is presented as a non-binding offer. This is necessary so that the worker does not feel patronized. Furthermore, wrong reactions of the system – i.e., the worker's intention was not predicted correctly and hence the system reacts in an undesired way – do not cause unnecessary disturbance as the worker is never explicitly interrupted in his work.

One example is well-known from navigation systems: if the user leaves the proposed path, the route is silently recalculated accounting for the deviation. Hence, the proactive help assures that the optimal path is always displayed without interrupting the user with error messages or commandments. Similarly, MICA does not interrupt the current workflow when it recognizes a deviation. Instead, it just highlights the help button, so that appropriate help can be obtained with a single click.

Concrete situations or problems are identified by observing the worker's actions. Systems' reactions rely on the analysis of the movement history. Hence, movement sensors and a positioning technology are necessary.

## **DIFFERENT EXPERIENCE LEVELS**

Calm computing makes it possible that experienced users are not interrupted by system alerts addressed to unskilled workers. They can work in the efficient ways they are familiar with. As Interaction-by-Doing facilitates implicit interaction, less explicit interaction forms have to be learned by users. This supports both, skilled and unskilled users. Proactive help is designed as a non-binding offer so that experienced workers are not disturbed. At the same time, unexperienced workers are thankful for the help when in need.

## **DEVELOPMENT METHODOLOGY OF MICA**

The first MICA project started in 2004 running until 2006. The goal of the project was to prototypically explore the possibilities of supporting humans in their every-day working environment using technologies like context-awareness and user modeling with mobile devices. For this exploration it did not matter what working environment that was.

The prototype served three purposes: firstly, it allowed us to gather first experiences with a variety of hardware and software technologies used in MICA. Secondly, it shows the technical feasibility of the concept. And thirdly, early feedback from potential users and customers can be collected. For example, it is possible to run user tests under laboratory conditions, or to show the prototype on trade fairs. This helps to review the general concept and shows opportunities for future development.

Depending on success and reception of the prototype, a second project can be set up.

For this successor the prototype is reworked, and a more mature pilot version is then tested in the field, i.e., in a productive environment.

## FIRST PROTOTYPE

As a first setting for MICA, a warehouse scenario was chosen, where MICA would assist warehouse workers in the picking process. However, the MICA architecture was not meant to be constrained to this specific setting but to be a platform for realizing very different scenarios. The major challenges of the first MICA prototype are:

- Workers need hands-free support,
- Interaction modalities for system input must fit the current situation and task,
- Volume levels of audio output must automatically adapt to environment noise levels,
- A display must react to rapidly changing lighting conditions, and
- The system must be highly responsive, never leaving the worker to wait for it.

MICA has to provide a combination of explicit and implicit interaction methods in blue-collar environments. It faces situations in which the spatial relations of objects change dynamically. Hence, the worker's environment has to be monitored and interpreted in real time. On the one hand, this enables MICA to identify a worker's need for help and to react on implicit interaction clues like stumbling or search behavior. On the other hand, workers interact explicitly with MICA, for example by pressing the "OK" button to confirm the execution of a proposed action after a warning message. In particular the combination of implicit and explicit interaction on various modalities leads to natural blended interaction (Eisenhauer, Lorenz, Zimmermann, Duong, & James, 2005).

MICA guides the worker through the warehouse, keeps track of articles picked (see Figure 7 b) and pro-actively offers help. The

following subsections give short descriptions of the different components of the original MICA system. At the same time, this section serves as a baseline for explaining the modifications of the MICA pilot in the next section. Both sections are therefore structured similarly, describing the necessary ingredients for Interaction-by-Doing like the MICA trolley, navigation, article identification, and the software design. This is followed by summaries of the realized concepts and the interaction experience. As a case study, the MICA prototype provided valuable lessons learned that were used to improve its successor, the second MICA (pilot).

## TROLLEY

The multi-modal interaction in MICA relies on a wide range of different sensors for retrieving implicit interaction information, an input device for providing explicit interaction possibilities and devices to give feedback to the worker; among these is pen-touch display, RFID readers and antennas, a WLAN data connection, and a high-performance CPU for coordinating all interaction devices in the worker's direct vicinity. Besides being heavy and bulky by themselves, the devices

also need a power supply large enough to keep the system running during a complete workday.

A device that workers use throughout the entire picking process is the trolley on which order boxes are placed. The trolley therefore became the heart of MICA hosting all the devices required, as one essential requirement is not to strain the worker in his work with heavy equipment.

## ARTICLE IDENTIFICATION

MICA receives picking orders from a server and lets workers select their next order. Workers – while always being connected to MICA via the picking trolley – are presented a picking list, which is automatically synchronized with the articles already picked.

For this, the MICA trolley is equipped with RFID technology which continuously monitors the items that are already picked. Articles and boxes (into which the articles are picked) are tagged with passive RFID tags. The floor of the MICA trolley is made up of a 4x4 array of RFID readers that read articles placed above them (see Figure 3). When an article or a box is placed on the trolley, MICA can determine if the article is correct and if it is placed in the right box. Hence, with MICA the worker is not constrained to work on one order at a time, but he may choose several orders and work on them simultaneously, while MICA makes sure that no article is wrong, forgotten or picked into a wrong shipping box.

Our RFID readers operate at High-frequency (approx. 14MHz, HFID) electromagnetic wave band, which has a limited reading range, but reveals good characteristics when used with conductive materials or liquids. This is important because the prototype is intended for office items (e.g., hole puncher) which occasionally contain metal or liquids. Diverting from the original plan, the MICA prototype only has a 1x2 array of RFID readers at the bottom. The reason is that the shape and diameter of an antenna affects the reach of the reader's field above the antenna. So their large size enables an elongated vertical read area up to 30cm above the trolley loading area, while limiting the maximum number of simultaneous orders that can be processed at a time to two.

In practice, it turns out that reading articles on a second layer above ground layer is unreliable. Articles randomly disappear or are attributed to the wrong box if an article is placed near the boundary of two adjacent RFID areas.

## NAVIGATION

MICA realizes an indoor navigation system to guide the worker to the next article on the picking list. Such navigation system essentially consists of two parts: A hardware part for determining the physical position of the worker, and a software part calculating and presenting a route.

Drafts for tracking mechanisms in MICA combined Ekahau - a low precision WLAN tracking - with fine grained ultra-wide band (UWB) tracking (Eisenhauer, Lorenz, Zimmermann, Duong, & James, 2005). However, the actual realization of the MICA prototype completely relied on WLAN tracking leaving aside other tracking technologies because of the high cost associated with equipping large areas with UWB tracking systems.

Given a list of articles the worker has to pick for his orders and storage locations of individual articles, the navigation system determines an optimal route for the worker through the warehouse. For this computation, the route calculation determines the distances between each pair of articles along valid paths in the warehouse with the A\* algorithm (Hart et al., 1968). In the next step locations are ordered so

Figure 3. RFID antenna array for identifying articles and their location on the MICA trolley



that the round trip that visits all locations has an optimal length. This sorting – known as the Traveling Salesman Problem (TSP) (Menger, 1932) – is solved with a brute-force algorithm that finds the optimal solution. This is the most expensive computation step with a complexity of  $O(n!)$ .

## SOFTWARE

MICA uses a bus concept for input and output data. The buses are based on a Jabber/XMPP (see Saint-Andre, 2004) instant messaging infrastructure. Collected data – for example, raw sensor data from pointing gestures – are refined into messages with MICA data – e.g., pointing direction and angle – and posted to a chat room, and thus forwarded to subscribed receivers in this room. Here, user modeling and dialog management servers pick up that data. Also connected to the bus are server components that provide databases, host navigation processing, manage users and trigger pro-active help. Having higher memory and processor requirements, these components are placed on a stationary machine providing enough resources for the software. Responses from server components are then posted on the output bus for rendering on user interfaces (Schneider, Lorenz, Zimmermann, & Eisenhauer, 2006). A known problem with Jabber is that the amount of network traffic grows exponentially with the number of participants in a room. The common bus is therefore split into several rooms so that the number of participants and messages in each room is less than that in one common room for all.

The XMPP protocol was chosen because of its openness and interoperability. Protocol implementations exist for different programming languages and platforms; even resource restricted mobile devices. For this resource thriftiness, Lorenz and Zimmermann (2006) embedded ARFF (<http://www.cs.waikato.ac.nz/~ml/weka/arff.html>) messages (containing the data sent by MICA subsystems) into the XMPP messages. ARFF messages have their own header containing sender and receiver information, and data specific to the command.

All components of the MICA server are implemented in a stand-alone Java application. On the client side, the GUI is implemented in C#. Originally the client included several intelligent functions, but due to high processor load and resulting low responsiveness of the GUI several functionalities were moved to the server. A light-weight client receiving detailed instructions remained.

## PRO-ACTIVE HELP

Kaufmann et al. (2007) interviewed and accompanied several workers and managers during their work in two non-automated warehouses. The aim was to get to know the authentic processes in a warehouse in order to identify situations where help was needed. Besides helping workers to avoid picking errors by observing picked articles, and helping them to find articles quicker by guiding them to the storage location, other stressing or time consuming activities were identified. Resulting from these, eight implicit interaction principles were developed that indicate if a worker is in need for help. These interaction principles are used as input to a finite state machine, which then triggers a means of pro-active help.

For example, a common situation was that an article was damaged or missing. When this happened the worker had to fetch the warehouse manager to show to him the situation. During this time, the picking process is effectively on hold for up to 30 minutes (as described in Section 2). For such situations, the MICA prototype includes a wireless headset and video camera so that the worker can remotely consult the warehouse manager without having to walk to her office (see Figure 4). One of the indicators is that a worker is looking about or moving his head horizontally in a noticeable way (i.e., scanning for a specific item). The video stream continuously generated by the helmet-mounted video conference camera was re-purposed to detect horizontal movements between individual video frames.

Other indicators used as input for the pro-active help system included a worker standing

still in the warehouse, the picking of a wrong item, or the worker walking too far away from his trolley in the wrong direction.

## MULTI-MODAL INTERACTION

Besides allowing graphical interaction with the worker, the client outputs speech like "Put two hole punchers into box A". The voice output is composed from sampled partial sentences, hence providing high quality output at the cost of flexibility and a higher cost for hiring professional speakers to speak the partial sentences, quantities and article names. By offering several output modalities, the chance of misunderstanding due to inappropriate environmental conditions like loud noise is reduced.

The MICA software architecture is a mix of centralized and distributed components. Input from different kinds of sensors is collected by MICA clients, fused with other sensor data on the same client, and filtered through a recognition mechanism. The pre-processed data is then published to a data bus on the local network that is used by MICA components (like sensors, servers, etc.) for their communication.

Besides touchscreen interaction, Interaction-by-Doing is offered as input modality. Each of the modalities is chosen for the correct situation. In the normal case of picking, the worker is situated beside the trolley, so that it is difficult to type on the touchscreen. Thus, Interaction-by-Doing is used. In cases where the worker has to go to the screen anyway, e.g., when video chatting with the overseer, touchscreen input is expected.

## LESSONS LEARNED FROM THE FIRST PROTOTYPE

The biggest problems we encountered were of physical nature. The batteries for power supply of the mobile components (e.g., RFID readers) have to be well proportioned. Long before the batteries are depleted, the readers' reliability begins to degrade. This adds to an already existing problem with the article identification.

The original assumption that every reader reads only the area above itself and not the area above another reader cannot be confirmed. The readers' electromagnetic fields overlap or even twist around each other when objects are brought into the field. Though some modern antennas' lobes have almost the desired shape in free space, it is impossible to prevent fields from getting distorted when there are obstacles. Similarly, the radio-based localization needed frequent recalibration in an ever-changing environment.

On the software side, unreliabilities in the WLAN connection caused problems with the XMPP-based communication bus infrastructure on. A disruption of connection meant that either messages in chat rooms were lost or that messages were delivered twice. This could mean that first a lot of outdated messages were delivered before current messages were received. This led to some confusion for the test persons.

Finally, there were some usability problems because the mobile PC used a pen input. Many people would have preferred to use their fingers and have larger buttons or active areas. However, much of the functionality in the prototype's interface was not needed.

## SECOND PROTOTYPE

After the first prototype of MICA proved its feasibility, a follow-up pilot project started in 2008. The goal was to evaluate the road capability of MICA as well as its usability and market potential. A pilot allows testing a design and making adjustments in time. It also shows if anything is missing and provides quantitative proof that the system has potential to succeed on the larger (full) scale.

For MICA, the new requirement of being suitable for productive use brought new challenges so that many aspects of the first prototype were re-engineered. Also, the scenario where MICA would be used (warehouse) was now fixed from the beginning.

With Antriebs- und Regeltechnik GmbH (ART), a medium-sized enterprise for testing MICA was found. Founded in 1955, 700 em-

*Figure 4. Warehouse worker with headset and a small video camera mounted on his hardhat*



employees in Germany, Romania and Poland develop machinery supplies for the manufacturing industry. MICA ran at the headquarters' central warehouse. ART faces the typical problems of non-automated warehouses, and at the same time is continuously looking for solutions that support their just-in-sequence and just-in-time services. ART actively supported and contributed to the pilot and assembled the new hand pallet truck at its workshop.

Compared to the warehouses of the first MICA prototype, the requirements at ART are a bit different. They produce many of their articles specifically for their customers in small quantities (sometimes only one single unit). So for them, even one error in tens of thousands of picking items is too much. Their warehouse is smaller with fewer workers, and a much friendlier atmosphere. Environmental conditions like lighting and noise levels are rather constant. Importantly, ART's products constitute a challenge for MICA's original article identification and positioning: most items mainly consist of metal parts, are stocked in metal shelves and are handled in metal baskets. This is a conceivably bad situation for RFID and WLAN tracking. The typical order includes several baskets that are interchangeable but have to be prepared in a fixed order.

These differences and the immanent productive use of MICA necessitated design changes that are discussed in the following sections.

## **THE MICA HAND PALLET TRUCK**

The working process at ART requires that two boxes stand side by side on a pallet, and can be stacked up to the fourth level at eye height. A finger touch enabled Tablet PC is mounted at common eye level. It is tiltable and turnable so that people can adjust it to their personal needs. Two batteries supply the Tablet PC and the RFID readers for article identification and positioning (see following sections). A standard power supply cable for charging ensures the easy recharge of batteries. Full charging takes four hours so that it fits well between two working shifts. A fully charged battery supplies energy for ten hours of MICA-enhanced work so that it lasts an entire shift without having to recharge.

The MICA hand pallet truck is resistant against impact and scratches, electronic parts are protected. It is as easy to use as a normal hand pallet truck and fulfills safety at work guidelines. At the same time, hardware costs do not endanger profitability of the whole system.

## NAVIGATION

The positioning engine of the MICA pilot requires a higher accuracy. It needs to identify each single stockyard, situated no more than 30cm apart from each other. Ekahau cannot assure this accuracy, especially in a metal flooded and constantly changing environment. Hence, we changed to RFID-based tracking: RFID tags, working on another frequency range as the article tags, are placed on the floor of the storehouse. A RFID reader mounted underneath the trolley scans these tags and gets the corresponding location from a database. Floor RFID tags are usually placed in holes in the floor. This is not possible at ART because of a special anti-static and expensive ground. Using special adhesive labels which are resistant against physical force, we avoided drilling holes.

As corridors are wider than the width of the hand pallet truck, we placed three tags in a row orthogonal to the corridor to guarantee reading a tag on any track the truck could move through the corridor. Each of these tags is associated with the same X/Y coordinates.

The worker's walking direction is derived from his current and previous positions. The new MICA system rotates the map so that viewing direction is always up as opposed to a fixed orientation with north always being up. Article locations are stored as their "true" location, which is not directly on the paths defined by corridors. Instead the articles are projected to the nearest path; the angle between projection vector and moving direction determines if an article is in the left or right hand shelf (see Figure 5). Additionally, now 3D map data may be annotated with individual path costs, therewith allowing to reduce traffic in selected corridors.

The brute-force path length optimization with NP-complete TSP from the first MICA performs unsatisfactorily when applied to a picking list with 20 or more different locations. But an approximation algorithm (the "nearest neighbor" algorithm) usually provides good results with an average length of 1,25 times the shortest possible route. In the worst case, the route is at most  $O(\log d)$  longer than the optimal

route (Rosenkrantz, Stearns, & Lewis, 1977). Its computational complexity at any given time is  $O(n)$  for sweeping through all the remaining article locations to find the article with the shortest distance to the current location. With a normal PC this means that planning for thousands of locations is possible without a noticeable delay.

## ARTICLE IDENTIFICATION

As the RFID readers of the first prototype were integrated in the trolley's bottom they occasionally failed to read articles on the second level. In the pilot setting this detection ratio is even lower due to the fact that articles are metallic. This requested a change in RFID technology, from HF to Ultra High Frequency (UHF). UHF is prevalent in logistical applications: besides worldwide standardization in ISO 18000-6C (EPC global) (ISO 18000-6C), it features long reading ranges, bulk reading of several transponders at favorable prices, and compact chip design.

Additionally, we need to be 100% sure that no article passes the scanner without being recognized. Picked articles appearing and disappearing randomly are obviously not acceptable. Also cross checking after picking is no option as it would entail no enhancement compared to the situation without MICA. Therefore, the RFID readers are mounted on a frame that is put on top of the boxes. These readers do not scan the contents of boxes, but register articles that are moved in and out of a box. The reading area is carefully calibrated to exactly cover the whole box opening. It thus assures that every passing article is read but nothing else from nearby shelves. This preserves a natural way of working and preserves valuable energy on the mobile device.

In order to identify the direction of movement of a transponder through the box opening we analyze the RSSI value (Receive Signal Strength Indication (IEEE, 802.11)) of the tag. The obtained value qualifies the received field strength of wireless communication applica-

tions and is transmitted by the reader for every reading event of a transponder. Mathematical calculations yield the information if movement is upwards or downwards when two readers are placed on top of each other.

For two boxes stand side by side on the pallet, two readers (for RSSI movement direction detection) cover each box opening. A frame carrying one pair of readers slides up and down the truck's mounting to rest on the rear stack of boxes. The second pair is attached to the front of the frame with its read area covering the front box opening (see Figure 6). The frame construction is quite heavy, but workers need to move it up to the fourth level of boxes (height of the head). Therefore, a bowden cable enables effortless moving.

Maintaining a continuous electromagnetic RFID field consumes much energy. This is too much for a battery powered device, particularly if there are five such readers (four for article identification and one for positioning). A way to reduce energy consumption is to turn off the field while no article is potentially in range. Built-in ultrasonic (US) sensors that consume negligible amounts of electricity are coupled with the readers and automatically trigger a reading process. The US sensors detect moving objects within a range of up to 70cm. Any object passing the sensor immediately turns on the reader that creates the electromagnetic read field within milliseconds. Every transponder within reading range is then read. Configuration and placement of the rear readers' triggers is carefully adjusted because US waves emitted by them would reflect from the back side of the front readers and trigger a read because the echo would mistakenly be interpreted as coming from an article. After a pre-defined period the reader switches back to standby. This method ensures that a reader only reads while an article is placed into a box or taken out of it. Thus the power consumption is reduced to a minimum, resulting in a higher operating time of the whole system.

Besides saving energy the trigger has two additional advantages:

- (i.) The already low probability of reading articles in the shelf is further reduced, because readers sleep most of the time, and
- (ii.) It is possible to identify if an article is not detected by RFID, in case of a broken RFID tag. In that case, the MICA system prompts the worker to re-pick the article and initiates a multi-step error correction process.

## PRO-ACTIVE HELP

Several indicators that were used for the pro-active help of the first MICA are no longer available. For example, the video conferencing is no longer necessary due to the warehouse size, and therefore the head-mounted camera is not available. Similarly, persons are no longer tracked and it is therefore impossible to detect if they wander away from their trolley. As a consequence of this, we concentrated our efforts on the reliability of the remaining areas of pro-active help, navigation support, article identification through article pictures and picking error correction.

## MULTI-MODAL INTERACTION

The constant environment in terms of lighting and noise within the warehouse makes a combination of auditive and visual output on the table PC most reasonable. Speech composition from partial sentences is not feasible anymore because there is an unlimited and dynamically changing space of possible wordings. The MICA pilot rather generates audio output with a text-to-speech engine allowing synthesizing any sentence from its written form. As ART has a complicated naming scheme for articles where each name is composed of 15 numbers and letters it makes no sense to spell this name. By referring to an article's stockyard instead, there is no danger the text-to-speech engine generates incomprehensible article names. The visual interface has been re-factored to present less information at once.

Figure 5. Picking article from right hand shelf



Menus and other complex explicit interaction constructs in the GUI have been removed because most workers have little computer experience. Instead, buttons and other active areas have been enlarged. The main interaction method, Interaction-by-Doing, remains: movement and picking still make up for most of the interaction between worker and MICA.

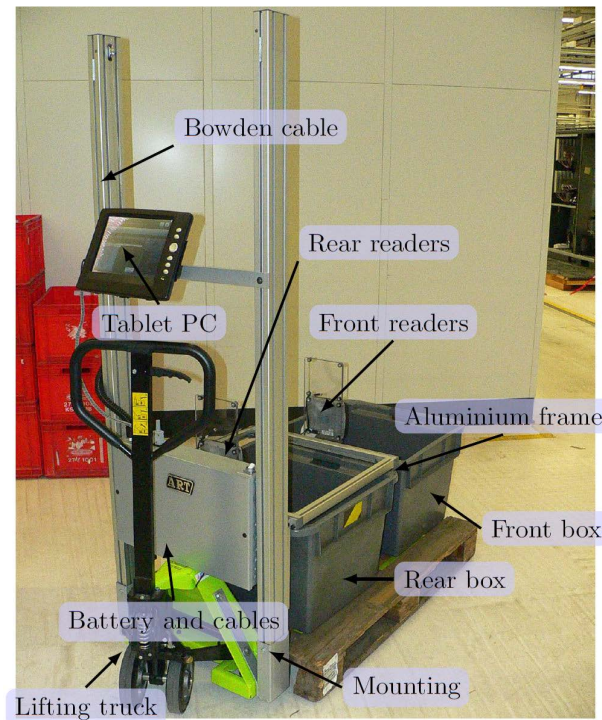
## SOFTWARE COMPONENTS

Building a system that is used in a productive environment requires higher diligence than building an experimental prototype serving only as a proof of concept. The first prototype was implemented with an architecture for a wide and diffuse application domain reflecting personal research interests. It was to be used under laboratory conditions. Implementation sprints with ad-hoc processes took place before trade fairs. Necessary cleaning-up and refactoring with reuse in mind would occur in the time in between, where deadlines were less troubled. This, however, did not happen. MICA was not suitable for field-testing. In preparation of the study, MICA's software sources experienced a general overhaul and large portions of MICA's code had to be rewritten from scratch by an all new team because scientists of the first prototype had changed to new projects.

Differently from its predecessor, the new MICA system is much more focused, and no longer a platform for studying multi-modal interaction and user modeling under different conditions. Instead it is fully aimed at the warehouse scenario. Usability and understandability to the common warehouse worker are the primary objectives. Also a higher degree of reliability is necessary to not disrupt daily work of the productive environment. However, one design goal is still to keep the MICA software open for using different hardware devices and software components with the system.

MICA's backbone - instant messaging based communication - is replaced by the Java Message Service (JMS), which provides enterprise-class reliability in message oriented architectures. JMS guarantees message delivery for the publish-subscribe model, thus replacing the chat room mechanism, where messages could get lost if a client temporarily disconnects from the chat room. Also messages are sent with a time to live, which prevents a flood of messages that could occur if a component reconnected to the message bus. To save bandwidth low-priority messages (like position updates) are discarded earlier in case of a transport bottleneck. As JMS is capable of transporting entire Java objects, the ARFF message encoding was mostly removed, leaving it only as an interface to the .NET GUI.

Figure 6. Lifting truck with boxes and RFID mounting of the second MICA pilot



The original monolithic server part is broken up into distributable components that communicate with each other through JMS messages, thus facilitating the relocation of individual components between different physical machines. The bus architecture is modified according to the observer design pattern: Every component (e. g., a worker location sensor) publishes its messages, while other components (e. g., navigation and route computation) subscribe to the update of components that they are interested in.

## THE EFFECTS OF MICA ON ART

The biggest change for ART resulted in the elimination of an explicit cross-check in their picking process: prior to the introduction of MICA, workers went through the repository with a shopping-cart-like trolley. They collected

articles, brought them to the shipping area, cross checked the articles, and put them into a new box on a pallet. Afterwards, they repeated all steps until the order was completed.

The manual cross checking process has now been replaced by MICA's tag identification during the picking process. A box-by-box cross-check to keep an overview is no longer needed. The old MICA trolley is replaced by a hand pallet truck equipped with MICA technology (see Figure 6). Thus, picking onto a pallet on the hand pallet truck accomplished in one step. This saves time compared to the former multi-step process.

One of MICA's software modules connects it to the SAP Warehouse Management server of ART. This real-time data link keeps stock lists up to date. When picking starts, the items of the order are marked as "reserved", and are immediately removed from stock when picking finishes. Formerly, there was no "reserved" state and updates would take hours. It was

Figure 7. a.) Original design in English, b.) SAP design in German for ART



possible that the last item of a kind was picked in a previous order, so that the next one could not complete although started. Stock outage is a frequent problem and requires that picking starts early with enough reserve time before delivery, so that the missing piece can become available again. Hence, MICA reduces the time reserved for picking and packing.

## USABILITY EVALUATION

We put a considerable amount of effort into the design of the MICA GUI. It underwent several changes in the last years (see Figure 7a and Figure 7b): internal design reviews, customization to the SAP design guide, translation from English to German, and an adaptation to ART processes. Finally, a usability study was conducted with ART warehouse workers.

A usability evaluation measures the extent to which users in their specific context can

achieve their goals effectively, efficient and satisfactorily (ISO 9241, 1998b). Effectiveness is put on level with usability. A product, system or software supports effective processing of a task, if it provides all functions needed by a user to completely achieve his goals. Beyond that it can be rated as efficient if its functions are operated accurately and effortless. Satisfaction with the product, system or software necessarily (but not sufficiently) results from the perceived easiness and intuitiveness to operate the system. This unfolds in a model of stages, which stimulates the presentation of results. Effectiveness constitutes a measure of the usability potential. Results of a user test represent the efficiency, and satisfaction is measured with a questionnaire depending on the sample size of the usability study. Tests like the Software Usability Measurement Inventory (SUMI) (Kirakowski & Corbett, 1993) are recommended for sample sizes above twelve users. With lower sample sizes, like in our case, a shorter questionnaire

provides a rough impression of the overall satisfaction. This, of course, is not statistically representative, but nevertheless delivers useful information for the usability assessment and suggestions for improvements.

We first conducted a participatory expert evaluation of the interface with three experts – which meant that all experts were accompanied by two testers – one taking notes and the other in dialog with the expert taking care that no action on the interface is left uncommented and all relevant aspects of the system have been covered. That means that the tests were conducted in close collaboration with experts with the “thinking aloud”-method (e.g., Nielsen, Clemmensen, & Yssing, 2002) and subsequent discussions. In this test we identified 51 violations of requirements for the design of dialogs (according to ISO 9241-10 (ISO 9241, 1998a)). Most problems were related to violations of conformity with user expectations, error tolerance, or self-descriptiveness. Additionally, we identified and eliminated screens, which had lost functions, like the registration screen.

The original plan arranged for testing eight workers. But due to time restrictions this evaluation had to be conducted prior to the full completion of the system. In particular tests with RFID-reader hardware and its interplay with the software were only partially completed. The evaluation of the MICA pilot was therefore conducted with a limited set of three more experienced workers. The main reason for this limitation was that the system still was not completely robust, and that there was a risk that it had to be rebooted.

The participants were tested with real picking orders. Each usability test consisted of a short introduction of the worker into the nature of the test and to the method of “thinking aloud”. The tests were always conducted with three investigators: one that constantly stimulated the worker to comment each of his actions and two that took notes and pictures. All critical incidents were then collected and analyzed according to ISO 9241-10 and their specific violation of the dialog requirements. At the end of the test the workers were asked to

complete a questionnaire measuring their satisfaction with the system. As expected this early testing revealed a potential for optimization. A series of critical incidents could be assigned to 69 violations of dialog requirements that limit the efficiency with respect to task completion (see Figure 8a). In particular a high number (20) of malfunctions occurred that limit the effectiveness of the MICA System. However, the tests also revealed many positive aspects of MICA where the participants distinctively emphasized an unqualified success in conformance with dialog principles, as well as eight malfunctions that were directly eliminated during the test (see Figure 8b).

The results of questionnaire and interview indicate a good satisfaction with MICA in spite of its malfunctions. Participants were confident that the system simplified their picking process, saved time and prevented errors. Specifically, they highlighted that search and identification of items in the picking process with the system was much easier, less error prone and much simpler than picking without MICA. The violations of dialog principles and identified malfunctions resulted in a revised version of MICA in the actual field-tests.

## EVALUATION OF EFFICIENCY

In this section we present results of the MICA evaluation based on (Gillmann, 2008). An economic evaluation of investments must always be based on solid investment appraisals. This in turn requires well evaluated data, describing the logistical process. Key economical measures of logistic systems are time, quality and cost. To evaluate these data, the MICA pilot is implemented and tested in the ART warehouse.

To measure potential quality improvement and time reduction, as well as potential cost reduction, the paper based manual picking process is benchmarked against a MICA supported picking process. In particular, process times and failure rates are monitored. To evaluate the impact of MICA as a support system for (particularly unskilled) workers, both the

manual picking process and the MICA supported picking process are tested with groups of skilled and unskilled workers. Skilled workers included all of the workers that worked in the respective ART warehouse (less than ten). A similar number of unskilled workers were brought into the warehouse either from other departments of the company or by us.

The workers in the evaluation worked on real orders that were finally shipped to customers. During the entire evaluation phase we accompanied workers in the warehouse, drawing maps of the paths they took and taking the picking times. In the MICA experimental groups, the warehouse's paper-based quality control procedures were carried out in parallel by an experienced worker in order to detect problems that MICA might not have detected. In all experimental groups, the orders were finally (after picking was completed) cross-checked by an experienced worker to ensure the quality of the delivery. The results of this were also recorded to check for quality improvements through MICA.

The duration of the evaluation phase was four months. The full time was sliced into multiple smaller time slots, each one to host one of the four variations (with MICA vs. without MICA, experienced vs. unexperienced).

One major customer of the warehouse in our study produces large industrial machines (several meters in size), who receives electrical components and cables in various sizes from ART. In our study we included all orders for one series of machines from this customer. Hence, this study is highly representative for such orders. Due to the high number of orders from this customer, it can in turn also be considered as representative for all of the warehouse's orders.

To accurately determine the efficiency of MICA, we additionally need to take into account the cost of processes implied by MICA (e.g., tagging of articles before they are stored), the monetary cost of MICA hardware like RFID, and potential maintenance costs due to hardware wearout. We use common investment appraisal methods (Tucker, 1963) to calculate economic sense and an investment risk for this specific case.

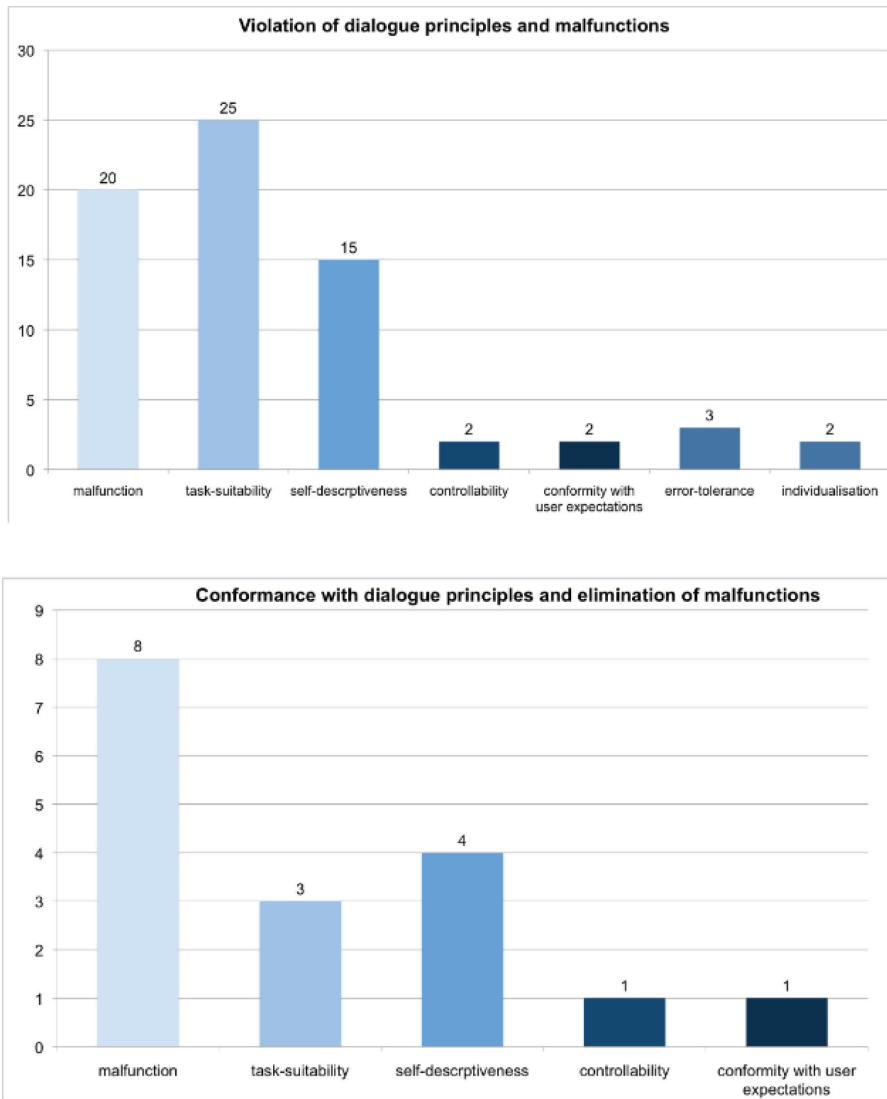
The overall picking process divides into four sub-processes: preparation, picking, inspection, and confirmation & hand over. Picking and inspection times depend on item quantities. Preparation and confirmation & hand over are independent of item quantities. Using MICA, the item dependent process time is reduced by 36%, when used by skilled workers, and by 75% when used by unskilled workers. A significant processing time reduction of 46%, for skilled workers and 61% for unskilled workers is demonstrated for the item independent process time (see Figure 9. Picking times are hidden due to data confidentiality).

The field trial focuses on two different error rates: error rate per order item ( $E_i$ ) and error rate per picking order ( $E_o$ ).  $E_i$  shows how many order items are picked mistakenly.  $E_o$  shows how many picking orders are processed mistakenly and in turn would result in a customer complaint. Without using MICA, the error rate per position is 0.48% / 4% (skilled / unskilled workers). More than this, a subsequent final cross-check of articles picked cannot detect all picking errors. Thus the error rate per order turns out to be 14.3% / 25% (skilled / unskilled workers). In contrast, with using MICA, all of the human errors are detected, thus the error rate per item and per order drops to 0%, for skilled and unskilled workers.

The investment costs divide into one-time expenses and operating costs. One-time expenses are, for example, expenses for hardware, software, and infrastructure. Furthermore, assuming a good "confidence" in inventory data, according to correct and real time confirmations, dispatching can be organized more efficiently, thus "safety stock" can be reduced, yielding additional cost savings.

Based on experimental data, investment in MICA reaches a ROI of 38% at a yearly picking quantity of approximately 80,000 items. A typical amortization time of 18 months is reached at a yearly picking quantity of approximately 280,000 items. MICA demonstrates a substantial reduction of processing times, as well as a zero picking failure rate, both with a group of skilled and unskilled workers. Additionally, unskilled workers using MICA reached a picking perfor-

Figure 8. a. Usability violations b. Usability conformance



mance almost as good as skilled workers. This shows very high potential of MICA for broad spread industrial use.

In summary, the evaluation shows that MICA successfully supports complex picking processes. Potential customers are companies with small to medium sized goods, each of medium to high value, with inhomogeneous order structures and with high overall picking quantities.

## ANALYSIS OF SALES POTENTIAL

In order to find out the potential of MICA for the market, we finally present an analysis of sales potential based on (Brauner, 2009). The sales potential is defined as the portion of the market potential that a particular firm can reasonably expect to achieve (Lucas, 1975). With

the analysis we address the question, how big the market is in the relevant industries.

As MICA is a new system, no reviews of existing similar systems can be taken into account. Instead, a questionnaire was distributed to 300 companies, 25 completed questionnaires were sent back. The amount of companies for which MICA can be useful is too large to contact them all. Because of that, a mix of random and quota selection was conducted (Schnell & Kreuter, 2003). As only particular employees of a company can answer the questions, we tried to contact experts via already existing contacts.

The questionnaire introduces the MICA systems and afterwards lets the probands reflect about their current picking system. Finally, the probands are asked if they consider buying a MICA-like system to determine the sales potential. About 17% consider buying a MICA-like system, so we assume the sales potential to be 17%.

According to the Bureau of Labor Statistics (2009) there are about 6,000 pickers in the US machinery industry. Hence, the sales potential for the US machinery industry is 17% of 6,000 = 1,020 MICA trolleys. We gathered the same information for the rest of the world and interpolated data where no data was available according to general economic performance data. In summary, we computed a sales potential of several ten thousand MICA-like trolleys for the whole world. Again concrete number are subject to data confidentiality but can be obtained from SAP on request.

## RELATED WORK

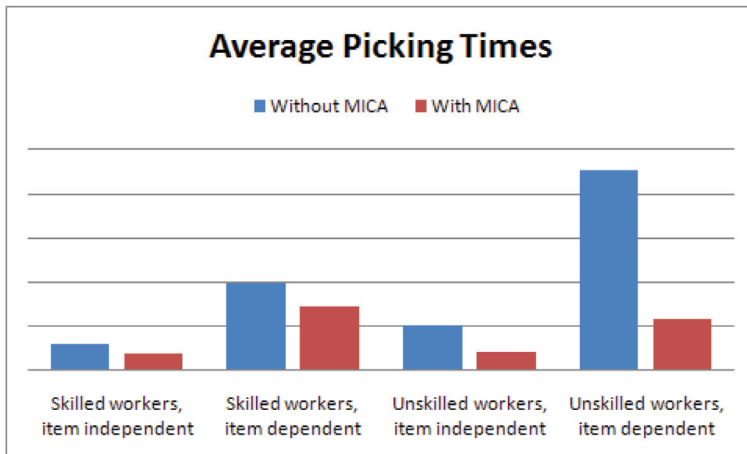
MICA combines in a single application context-awareness and RFID technology. On the one hand, its context-awareness is quite similar to that of systems like Oppermann and Specht (2000), Eckel (2001) or Long et al. (1996). These systems determine the physical context of the user from his location and orientation in order to provide him with useful information about his surrounding, i.e. exhibits in a museum or sights in tourism, respectively. In contrast,

MICA is multi-modal, deals with a changing environment, and uses a set of different sensors to obtain context information. It does not only provide plain situational information but assists the worker with his current task. With respect to this, it is more like the context-aware assistants of Dey et al. (1999), Yan and Selker (2000) or Rhodes (1997). MICA, however, also serves a logistical assurance objective by guaranteeing that picking errors do not occur. MICA also has some aspects in common with smart shopping applications like that from Asthana et al. (1994) because it helps the user to locate items and guides him to their storage location.

On the other hand, RFID is attracting more and more attention in business environments as it provides an interface between the physical world and an enterprise's information infrastructure (Want, 20004). A major role in the business environment plays logistics, where the tracking of goods and their delivery status are traditional applications (Weinstein, 2005). Companies use huge RFID gates on the entrance and exit areas of their warehouses to automatically register incoming and outgoing goods while these are still loaded on trucks (Lefebvre, Lefebvre, Bendavid, Wamba, & Boeck, 2006). Historically, RFID technology and tags were too expensive to track individual items. As prices for tags have recently dropped significantly, even item level tracking of low-price goods becomes possible. Bendavid et al. (2006) present a study where a RFID-based single-item hand-over between customer and supplier is analyzed under laboratory conditions. Yet their system does not provide support or detect errors during the picking process. With this respect, RFID-enabled shopping carts are what comes closest to MICA's article tracking (e.g., Kourouthanassis, 2003). For RFID-based locating Luimula et al. (2010) use a similar approach but as MICA is operated by humans, obstacle tagging is not necessary.

Unlike other system like the IBM MAGIC system, which uses gaze tracking for the prediction of cursor movement (Zhai, 1999), in MICA a combination of speech and pen input with user movement in a physical environment

Figure 9. Average picking process times



was favored. MICA, as opposed to many other multi-modal applications, has prominent physical parts that have original practical reasons: the trolley is already there so that the worker does not need to carry the items himself. Only article and box identification are added but they do not change the natural way of working. Likewise, the worker would be moving in physical space also without MICA. This observation is the basis for Interaction-by-Doing.

## CONCLUSION

We presented a support system for warehouse workers: its requirements, the Interaction-by-Doing design principle, its evolution through prototype and pilot, and evaluations of usability, effectiveness and sales potential.

The MICA prototype is successful as a proof of concept. The reworked MICA pilot proves successful in field-tests, where it measurably supports warehouse workers in the picking process. Thanks to multi-modal interaction MICA is applicable to the changing environments of a warehouse. Calm computing principles and pro-active help make it usable for unskilled workers as well as for experienced workers without having to interrupt the familiar way of working. Intuitive handling as

well as support for every worker's experience level is assured by the Interaction-by-Doing concept. Pro-active help prevents errors before they occur.

During its evaluation, several parts of MICA were adapted and improved. The positioning system is enhanced from WLAN-based to RFID-based technology, thus increasing its accuracy when identifying a single stockyard. The new RFID-enabled hand pallet truck frame proves to scan 100% of the picked articles without interfering with the usual way of working. At the same time, no articles from the repository are accidentally read. The frame fulfills the picking process requirements of the ART warehouse and could be adapted to the needs of other warehouses.

The usability evaluation reveals that search and identification of articles is much improved with MICA. The results already indicate a good satisfaction with MICA in spite of still existing malfunctions. Participants are confident that the system would simplify their picking process, save time and prevent errors. It can be expected that the new introduced interaction concepts and an improved MICA system that overcomes the detected malfunctions and violations of dialog principles will fully satisfy users' needs.

MICA's potential to reduce the number of errors and to speed-up picking processes

in non-automated warehouses is shown in the economic evaluation. Enterprises with high picking quantities are offered a high potential to reduce costs. During economic peak times MICA helps as well unskilled workers to reduce picking errors even under high time pressure. The analysis of sales potential shows that there is a market for MICA-like systems.

The future work consists of transforming the pilot into a productive system. For this, mainly stability must be enhanced and errors have to be found in high-pressure tests. Besides software errors, the reliability of the RFID reading has to be checked. Multi-modality can be advanced to more modalities as in the current status. However, MICA's future also depends on economic decisions of companies that traditionally have conservative customers.

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