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A Ubiquitous Computing Environment for Aircraft Maintenance

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Abstract
Ubiquitous Computing bears a high potential in the area of aircraft maintenance. Extensive requirements regarding quality, safety, and documentation as well as high costs for having aircrafts idle during maintenance demand for an efficient execution of the process. Major weaknesses that impact the efficiency of the process are an inadequate tool management, human errors, and labour intensive manual documentation and check procedures. In this paper we propose a solution using ubiquitous computing technologies that improves aircraft maintenance and provides a high level of usability. A scenario, a systems architecture, and maintenance applications are presented. The Smart Toolbox and the Smart Tool Inventory were implemented as proof of concept.

1. Introduction

For maintenance, repair, and overhaul (MRO) of aircrafts, strict regulations define requirements for quality, safety, and documentation. These are the reasons why the general process is largely standardized within the industry [3]. Most MRO events are executed preemptive. For passenger aircrafts, base checks are required approx. every 650 flying hours. MRO costs are corresponding to 12% of the total operating costs of an aircraft. During maintenance of commercially used aircrafts the owner faces high opportunity costs. The costs of having planes idle during unplanned maintenance are estimated at US-$ 23,000 per hour [5]. For these reasons competitive advantages can be achieved by carefully planning maintenance events and making the execution of MRO more efficient.

In this paper we propose the usage of ubiquitous computing (Ubicomp) technologies in the area of aircraft maintenance and present a scenario and architecture that deploys these technologies to improve the efficiency of MRO processes. The solution is based on the concept of movable asset management as presented in [19] and is the result of our practical experience from a project that was carried out in cooperation with an aircraft company[1] and SAP CI. During the project prototypes were implemented as proof of concept.

An important part of the vision of Ubicomp is the seamless connection of the physical world with its representations in information systems [20,27]. Ubicomp technologies like automatic identification, sensor networks, localization, and mobile communication enable smart objects that have a unique ID, are context aware, have a memory, and are able to communicate [10]. Smart objects

[1] Called “Aircraft Corp.” in this paper.

have the potential to improve business processes and create new business models [9,11,24]. However, limited research work has been conducted in the field of industrial applications of Ubicomp. In the area of aircraft maintenance the application of wearables was examined in [7,22] and can be incorporated into our solution. Our approach does not only focus on a single application but describes a Ubicomp environment similar to the approach that was presented in [17] for retail. Other institutions that also focus on applied Ubicomp and presented prototypes for various application areas are Accenture [2], Georgia Tech Institute [1], IBM [15], M-Lab [6] and TeCo [25].

Following to the introduction, Section 2 describes the weaknesses of the traditional MRO process at Aircraft Corp. with a focus on tool management that has a major impact on the overall process efficiency. Section 3 presents a scenario that shows how the MRO process can be improved using Ubicomp technologies. In addition, a systems architecture realizing the scenario is presented. Section 4 closes with a summary of challenges in adopting the proposed MRO architecture and its possible future extensions.

2. The MRO Process

All MRO events are carried out in an aircraft hangar where several mechanics work together on one airplane. Each mechanic has his personal toolbox including a set of typically used tools. Additional tools can be checked out from a central tool inventory. The Maintenance Review Boards (MRBs) of the manufacturers that describe maintenance procedures for different parts can be found in the handbook library. All documentation that is recorded during MRO are stored on a central desktop either in paper or in electronic form using a personal computer. Special shelves are used to store dismantled, repaired, and spare parts (see Figure 1).

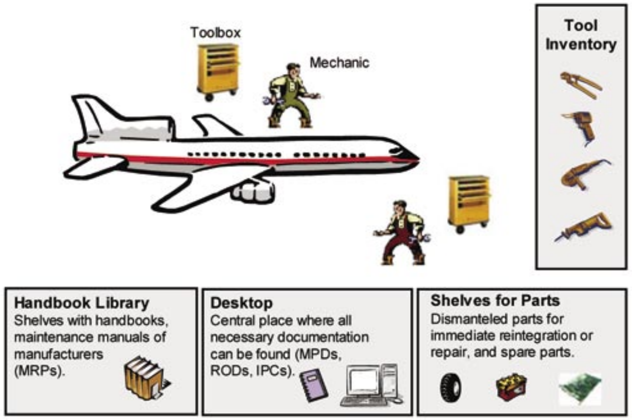

Fig. 1: The traditional aircraft MRO environment

The MRO process comprises the following main steps:

- **Customer order and planning.** A MRO event is initiated with the customer order. At an agreed date the plane is brought to the hangar and the relevant documents (logbooks) are handed over to the service center. The logbooks contain information about flying hours, operating hours, starts and landings, condition of the plane and its parts as well as complaints. Based on this information the MRO tasks are planned. Some of these data were recorded automatically (e.g. flying hours), others were recorded by the pilots or owners of the plane (e.g.. starts and landings, complaints) or during the last MRO. This holds the potential of inaccuracy (e.g. valuations) or human errors. The planning is recorded in the Maintenance Planning Document (MPD) that describes the MRO tasks and for each task the necessary activities.

- **Procurement of parts and tools.** Based on the MPD, the necessary parts and tools are determined. Missing parts can be ordered from the procurement center by using the Illustrated Parts Catalogue (IPC). Special tools can be checked out from a central tool inventory. Missing spare parts, long delivery times for parts, or misplaced tools can delay the MRO process.
- **Carry out MRO actions.** The MRO activities are carried out according to the MPD. Some failures are only discovered in this step, which makes it necessary to complete the MPD and procure additional spare parts or tools. The mechanics use a PC to record all activities they carry out in the discrepancies report (ROD). For each activity the mechanics identify all parts that are subject to inspection, replacement, or repair by its serial number and describe the status of the part. The duration of the task is documented as well. The correct inspection procedures for the parts need to be looked up in the MRBs that are only available in printed form. This task is very time consuming and it is assumed that sometimes the mechanics forget it.
- **Control and delivery.** Once the MRO is completed, an inspector checks the result. The inspector fills up an "Aircraft Certificate of Release to Service and Maintenance Statement" that describes all checks that were carried out, the repairs that were done, and the parts that were replaced. Finally, the plane is delivered to the customer.

Major weaknesses have been identified that can delay the delivery or have an impact on the quality of the result: It is estimated that mechanics spend 15-20% of their time with searching for tools or documentation [21]. Doing documentation manually is cumbersome and holds the potential for human errors. Incorrect documentation can cause problems during planning of following maintenance events. Forgotten checks of the MRBs can also lead to errors that can affect the safety of the airplane. In the following section, the weaknesses in tool management that have a major impact on the efficiency of MRO are analyzed in more detail.

2.1 Tool Management

Tools are stored in the tool inventory or in the personal toolboxes of the mechanics. Each mechanic is personally liable for the tools in his toolbox; for example in case of loss he needs to pay for the tools. The mechanic is also liable for any damage that is caused by a tool that was forgotten in an airplane. Since regulations state after which period a tool has to be exchanged or maintained, all tools must be uniquely identifiable. The following labour intensive and cumbersome tasks could be identified:

- **Marking.** Tools in a new toolbox are marked with the identification number of the toolbox. This task is done manually and can take up to two days. Since the markings often fade they need to be redone at least every two years.
- **Routine completeness check.** After each maintenance task, the mechanic is required to check the completeness and correctness of the toolbox. This means the mechanic has to check whether all tools are in the box and no tools were exchanged with colleagues. Therefore he needs to check the IDs on the tools.
- **Base completeness check.** Once a week each mechanic has to perform a cross check of his toolbox together with a colleague. This procedure can take several hours. Both completeness and correctness of all tools has to be checked. A tool list acts as a written protocol to facilitate the check and needs to be signed after completion.
- **Lookup.** If a tool is missing after a maintenance task, the aircraft in question needs to be checked until the tool is found. This can lead to a delayed delivery of the aircraft.

The tools in the tool inventory are stored in automated shelves and a service operator is taking requests for tools from mechanics. Every mechanic can have up to 10 tools checked out at the same time. To ensure this limit, a tool is handed out to a mechanic in exchange for a metal token that has the personal identification number of the mechanic inscribed. The operator carries out the following three tasks:

- **Checkout.** If a mechanic requests a tool that is not available, the operator can identify the mechanic who has checked out the tool by the identification number of the metal token, which is in the shelf position of the tool. If the tool is available, it is handed over to the mechanic in exchange for a metal token.
- **Return.** In exchange for the returned tools, the mechanic gets his metal tokens back. The service operator receives the tool and puts it back to the respective shelf position. Often tools are returned late and are not available to other mechanics since there is no accessible information about the tools that mechanics have checked out.
- **Lookup.** Sometimes mechanics need to know what tools they have checked out. In this case the service operator must search for the tokens of the mechanic on all shelves. This is a labor-intensive task.

The weaknesses in these tasks are based on missing documentation of checkouts and human errors. This leads to searching for tools that are checked out, misplaced tokens, exchanged tools, forgotten completeness checks and time consuming tool marking. If searching for a missing tool after MRO delays the delivery of the aircraft, this may results in costly penalties. As no data is available about tool usage, maintenance of tools is only be done based on manual inspection. Sometimes problems are only discovered during usage, causing safety risks and delays. To ensure that enough tools are available, costly safety stocks are kept. Stocks could be reduced based on usage statistics and by ensuring that mechanics return tools as soon as possible to the tool inventory.

3. A Ubicomp Solution to MRO

We propose the following solution architecture using Ubicomp technologies to improve the efficiency of the MRO processes and present two Ubicomp tool management applications which were implemented as part of the project: A demonstrator illustrating the concept of the Smart Toolbox and a prototype application of the Smart Tool Inventory. To give an idea about the benefits of the solution, a scenario describing the improved MRO processes from a mechanic's point of view is presented.

3.1 Architecture

As shown in Figure 2, in the digital world, the envisioned Ubicomp aircraft MRO architecture consists of three layers that access the central tool, mechanic, and storage data: the Ubicomp Infrastructure, the Enterprise Resource Planning (ERP) Systems, and the MRO applications, which are described below. In the physical world, tools and parts are tagged using Auto-ID technologies such as Radio Frequency Identification (RFID), which is one of the major technologies that are frequently discussed in the area of Ubicomp [26]. This allows applications to reach out into the physical world and seamlessly integrate into the MRO processes.

3.1.1 Smart Objects and Devices

Objects in the real world such as toolboxes, tools, and parts become smart [14] since they can be identified, may have sensors, store information about themselves, and are able to communicate. For example, the smart toolbox is able to sense its content and communicate its state to the mechanic, or tools are able to notify the mechanic about upcoming maintenance. The smartness is achieved by computation and sensing capabilities on the object, which in the simplest case can be an electronic identifier, and knowledge about the object in the Ubicomp infrastructure.

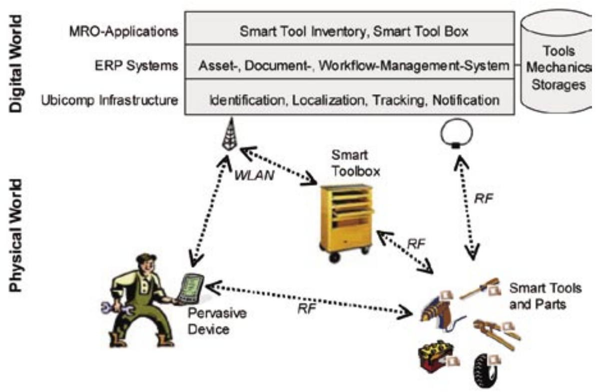

Fig. 2: Envisioned aircraft MRO architecture

To integrate the mechanic into the Ubicomp MRO environment, he carries his PD. This allows him to communicate with the smart objects, access data from the information repositories such as the handbooks of the tool manufacturer, automatically compile reports, and enables the Ubicomp infrastructure to notify him about any exceptional events or requests as illustrated in the scenario in Section 3.2. The PD could be any device that fulfills the following requirements: (a) the PD must have a wireless connection to the Ubicomp infrastructure, (b) it requires a certain amount of computational capabilities to autonomously execute application, (c) it needs a user interface that allows communicating or displaying information to the mechanic and receive information from the mechanic, (d) a device capable of identifying or communicating with the smart objects has to be included, and (e) the usability of the PD has to be optimized to unobtrusively integrate into the MRO tasks, which includes issues such as size, weight, or power consumption. For example, the PD could be a personal digital assistant equipped with speech recognition, Auto-ID, and wireless communication technology or a wearable device such as a headgear using augmented reality technologies.

3.1.2 Ubicomp Infrastructure

The *Ubicomp infrastructure* is the core of the solution architecture that enables the integration of the digital and the physical world. It provides several services to applications using the infrastructure including (a) identification of smart objects and mechanics, (b) tracking, and (c) localization of smart objects, and (d) notification of mechanics through their PD. To enable these services, a wireless communication infrastructure is necessary such as Wireless LAN (WLAN). In addition, Auto-ID sensors in the physical environment are required, which could be implemented using RFID technology by attaching tags to tools and parts to be able to identify them. With an infrastructure of reading devices in place they can be tracked and localized. The state of the smart objects is stored in the Ubicomp infrastructure and propagated to the Asset Management System if required. The communication of smart objects between each other or with the mechanic is performed by the Ubicomp infrastructure triggered by predefined business rules.

There are several Ubicomp and Auto-ID infrastructures in the research community that could be used in this architecture such as Gaia [23], NEXUS [13], Ubicomp Smart Identification Framework [8], Savant [4], Smart Items Infrastructure [18]. We are in the process of implementing the proposed architecture using the Ubicomp Smart Identification Framework since it supports RFID as Auto-ID technology in a straightforward manner and models smart objects in an extensible way.

3.1.3 ERP Systems

The *Enterprise Resource Planning* (ERP) systems are the next layer that consists of the Asset, Document, and Workflow Management System. The *Asset Management System* provides access to all information related to the physical objects such as toolboxes, tools and parts. The *Document Management System* stores the electronic versions of the MRPs and any other forms or documents that are needed for the MRO process such as the MPDs and RODs. Digital signatures can be attached to all documents. Finally, the *Workflow Management System* administers the MRO process and controls the sequence of tasks and activities as described in Section 2. It guides the mechanics through their tasks as defined in the MPDs utilizing their PD as a user interface. It also automatically triggers checkout requests for special tools and procurement of parts.

3.1.4 MRO Applications

The tool management is supported by the following two applications that are based on smart objects: The Smart Toolbox and the Smart Tool Inventory, which are built on top of the Ubicomp infrastructure and the ERP Systems.

Smart Toolbox

The Smart Toolbox is designed to automate the required completeness checks of the tools and notify the mechanic if tools are missing or if wrong tools are located in the toolbox. It mainly operates autonomously, however it communicates with the Ubicomp Infrastructure using WLAN to send reports of checks and tool usages.

The core functionality of the Smart Toolbox is the automatic and unobtrusive content monitoring using Auto-ID technology such as RFID. The Smart Toolbox is able to uniquely identify all tools that are in the toolbox. Based on the core functionality, the Smart Toolbox automatically performs the routine and base completeness check by comparing all identifications of the tools with the identifications of all tools that belong into the box. This also allows identifying tools that were put into the wrong toolbox. Another benefit is the usage history of the tools that is inferred by keeping the times a mechanic takes out a tool and puts it back in. This data is sent to the Ubicomp infrastructure and stored in the Asset Management System to be able to notify the mechanic about the next maintenance or exchange of a tool.

It is important to emphasize that the Smart Toolbox seamlessly integrates into the MRO process and that the way the mechanic is used to handle the tools and the toolbox does not change. The automatic monitoring happens unobtrusively relieving the mechanic of annoying checking procedures and the mechanic is only notified in the case of exceptions such as missing or wrong tools. In addition to a detailed notification, which is sent to his pervasive device, the state of the toolbox is visualized using a traffic-light display that shows whether the toolbox is complete or not.

Smart Tool Inventory

The Smart Tool Inventory enables mechanics to perform self-checkout and return of special tools from the tool inventory without any human interaction. Similar to the Smart Toolbox, all tools and mechanics are uniquely identified using Auto-ID technology. To avoid misplaced tools in the tool storage, tools are requested by a mechanic using his pervasive device and the tool inventory automatically delivers the tools to the checkout box after the mechanic is identified. If the checkout of special tools is known already in the planning step, they are requested automatically and scheduled for pickup at the time the MRO tasks is supposed to begin. Tools that are placed in the return box are automatically marked as returned in the system. The lookup process can be performed by a mechanic himself using the tool lookup service of the tool inventory accessible through his PD. The Automatic Tool Inventory uses the Ubicomp infrastructure to perform the identification of tools and mechanics, handle the requests of tools from the PD, and deliver the notification to the mechanic about return or pickup requests.

3.2 Scenario

The following scenario describes a typical MRO process in an aircraft maintenance environment using the proposed ubicomp MRO architecture. Each mechanic has a personal Pervasive Device (PD) that is for him the only visible component of the system architecture. The PD acts as a user interface and contains all the important applications the mechanic needs.

At the beginning of a MRO task, the PD notifies the mechanic about the work order that includes the plane that is subject to MRO and the spare parts and special tools that are needed. After skimming through the notification and possibly making some adjustments, the mechanic obtains the special tools at the smart tool inventory. Since the tool management system already requested the tools for checkout, the mechanic only needs to pick them up after being identified through his PD, without manually requesting the tools. After having checked out the tools, the mechanic picks up the necessary parts at the designated shelves. When taking the parts, his PD verifies that he only takes the right parts. By moving the PD close to a part, it displays the part information and indicates whether the part is on the list of parts that are needed for the MRO task.

After having obtained the necessary parts and tools, the mechanic starts to carry out the MRO task. His PD guides him through the whole process by displaying a list of all activities for the different steps of the task. Since the mechanic is required to read the inspection procedures for the different parts before beginning an action, the PD displays the relevant sections from the handbooks of the part manufactures. To ensure that he reads the sections, he has to confirm this by either pressing a button or using a voice command. For each activity, the mechanic identifies all parts that are subject to inspection, replacement, or repair using his PD. The PD displays a maintenance history and status report of the parts. The mechanic then describes the status of the parts dictating it to his PD. This information is automatically inserted into the ROD that is automatically generated while performing the activities of the task.

At the end of the task, the mechanic confirms its completion using the PD. The ROD is stored in the system and the inspector receives a message that contains the ROD with a request to check the results. After he confirmed the completion of the task, the “Aircraft Certificate of Release to Service and Maintenance Statement” is created electronically holding a digital signature of the inspector. The PD prompts the mechanic to put back all tools he took out of his toolbox. If the mechanic by mistake puts back a tool of a coworker, he immediately gets an alert message displayed on his PD telling him which tool was placed in the wrong toolbox. The PD also asks the mechanic to return all special tools to the tool inventory. This can simply be done by dropping the tools in the return box of the automatic tool inventory.

4. Proof of Concept

During the project with Aircraft Corp, we implemented the Smart Toolbox demonstrator and the Smart Tool Inventory prototype to show the feasibility of the proposed ubicomp MRO solution. In detail, the usage of passive RFID and the connection to an infrastructure and existing ERP system were explored.

4.1 Smart Toolbox Demonstrator

The Smart Toolbox demonstrator [12] uses passive RFID technology, which has the advantage of small and cheap RFID tags and a low read range thereby only detecting tools in the box. RFID tags are attached to all tools and the toolbox is equipped with an RFID antenna and reader. To be able to uniquely identify the tools and perform the completeness checks, the serial number of a tool together with the serial number of its toolbox are written on the RFID tag. The demonstrator visualizes the state of the toolbox (see Figure 3) in two ways corresponding to the two conditions: (a) Missing tools are shown by empty spaces, and (b) tools that belong to a different toolbox are highlighted with a special indicator. A similar form of the user interface could be sent to the PD.

Fig. 3: Setup and screenshot of the Smart Toolbox demonstrator

We identified the following challenges for a real world implementation of the Smart Toolbox: (a) Most of the tools are made out of metal requiring specialized RFID hardware (e.g. low frequency, passive RFID systems or ferrite coated tags), (b) the toolbox itself is made out of metal, which can be dealt with by placing RFID antennas in each drawer of the toolbox, and (c) some of the tools have a small size, which makes it difficult to attach RFID tags.

4.2 Smart Tool Inventory Prototype

The Smart Tool Inventory prototype is the first step towards a self-checkout tool inventory. However, the storage and delivery of tools is still done by a service operator who handles the tool requests. RFID tags are attached to all tools in the tool inventory and a RFID reader and antenna is placed in the checkout counter of the tool inventory (see No. 1 in Figure 4). The RFID hardware allows to uniquely identify tools that are placed on the checkout counter. No explicit user interaction with the system by the service operator is needed, since the tools trigger all processes: If a tool is placed on the counter, its identification is checked in the tool management system. If the tool is currently checked out, a return process is initiated and the identified tools are marked as returned in the tool management system, otherwise a checkout process is initiated where the tools are marked as checked out by the identified mechanic in the tool management system. In addition, a visual feedback about the process is given to the service operator (see No. 2 in Figure 4).

The implementation consists of three parts, (a) the Auto-ID infrastructure that performs the identification of the tools and mechanics, (b) the client application that receives the identification events and manages the checkout and return process, and (c) the Web application that allows the service operator to access information about the checkout state of tools. The client application is connected via the intranet to the tool management system. In this prototype, the tool management system is implemented on a SAP Web Application Server and the connection is done using the Business Connector interface. The data to and from the client application is sent as XML messages.

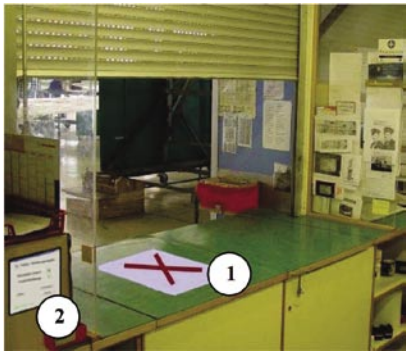

Fig. 4: Smart Tool Inventory setting with RFID reader and antenna (1) and display (2)

4.3 Potential Benefits

The ubicomp solution to MRO that is described above results in a more efficient and reliable MRO process compared to the traditional process that is described in Section 2. In this scenario delays and human errors are avoided, documentation is automated, resources are used in an efficient manner, and a high level of usability is achieved:

- *Avoidance of delays.* Carefully planning under consideration of the available resources helps to prevent delays during the MRO task. Tools and parts are prepared in advance, which reduces time for procurement. Search actions for parts, tools or documents are eliminated. Delays because of broken tools are avoided by preventive maintenance of tools. As a result, aircrafts can be delivered earlier while the risk for costly unplanned overtime is minimized.
- Avoidance of human errors. Human errors are prevented because the mechanic is guided by his PD that makes sure that the right actions are taken, the right parts and tools are used, and no tools get misplaced and forgotten in the aircraft. This results in higher quality and security.
- *Automation of documentation.* MRO actions, tool usage, and completeness checks are documented automatically. This ensures accuracy and completeness while reducing cumbersome manual tasks caused by paper-based documentation. As a result, legal requirements are enforced and accurate documentation improves planning of the following MRO tasks.
- *Efficient use of resources.* The use of mechanics, parts, and tools is planned and monitored. This helps to minimize unproductive tasks like searching, waiting, and doing paperwork. As tool usage is tracked and tools are returned immediately after usage, the stocks in the tool inventory can be optimized. This helps to cut costs for tools that are used infrequently.
- *Usability.* The technology supports MRO in an unobtrusive way. The mechanic can concentrate on MRO activities while different systems are working together in the background to ease tasks related to documentation, tool management, and part procurement. The PD is an easy to use multifunctional device that the mechanic always carries and that supports him seamlessly with all tasks, for example, MRO guidance, personal identification, and identification of parts and tools.

5. Conclusion and Outlook

The scenario that is presented in this paper shows that Ubicomp technologies bear a high potential to improve aircraft MRO processes. The proposed solution ensures that the regulations regarding quality, safety, and documentation are kept, the process is executed efficiently, resources are used in an efficient way, and unplanned maintenance time is minimized. The technology that is used for the systems architecture acts in the background. Traditional ERP systems are connected with pervasive devices and smart objects using a Ubicomp infrastructure in order to support the MRO process in an unobtrusive way. The PD acts as a one-for-all multifunctional device and functions as a single interface between the mechanic and the system.

We demonstrated the feasibility of the implementation of the architecture with the Smart Toolbox and the Smart Tool Inventory. From our experience, we discovered the following challenges: (a) RFID technology has some drawbacks in metal environments, which can be addressed, however, using specialized low frequency (e.g. 125 kHz) passive RFID systems. However, possible frequency disturbance, which is typical for a noisy (RE) industrial maintenance environment, has to be checked to be able to optimize read results. In addition, RFID and tool engineering know-how is needed concerning the processes of integrating robust RFID tags into tools, which also includes finding appropriate RFID tags for small tools. (b) Ubicomp infrastructures currently do not use any standards for the integration of Auto-ID technologies or for the modeling of smart objects, which requires additional integration efforts to incorporate such infrastructures into our architecture. c) In this paper we were focusing on the closed environment of Aircraft Corp. The scenario is only technically and economically feasible if all part and tool manufacturers use the same standards for product identification [16], which could be achieved using the ubiquitous Auto-ID infrastructure that is currently developed by the Auto-ID Center at MIT. This concept not only focuses on numbering schema but also on technical aspects and middleware concepts.

Further research needs to be done to generalize the presented architecture to be applicable in different asset management scenarios, which would include the specifications for the base functions and services in an Ubicomp infrastructure that are essential for optimization of asset management.

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