Case Study of Wearable Computing for Aircraft Maintenance

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Abstract. In this paper we present a concept for a combination of wearable computing and knowledge management with the goal to shorten the maintenance process in the aircraft industry. This research is part of an ongoing project which is carried out in cooperation with an aircraft company. This paper describes the functions of the wearable devices as well as the conceptual realization.

1 Introduction

Todays airline industry is under high cost pressure and is therefore interested in aircrafts that can be operated in an efficient manner. In the recent years, aircraft industry has put many development efforts e.g. into fuel economy of aircraft engines. But additionally, the efficiency of an aircraft is not only determined by its in-flight efficiency but also by the amount of time the aircraft is operated transporting passengers compared to the time an aircraft is on the ground, boarding passengers, undergoing maintenance, refueling and restocking. Therefore, the goal for the aircraft industry is to enhance the efficiency of aircraft operation by enhancing ground procedures. Moreover, with the new class of large aircrafts with over 500 passengers, either more cabin crew members are needed or cabin crew procedures have to be enhanced.

For both challenges, we propose the use of wearable technology. In a project with a major aircraft manufacturer, we have evaluated the current aircraft operating procedures with respect to the application of wearable computing and have identified a number of procedures that can be enhanced. From this, we have derived the specification of a wearable system that is now about to be implemented.

The specification contains two use case scenarios: in-flight cabin crew procedures and on-ground maintenance procedures. In this paper, we will describe our findings on the maintenance procedures use case. The general goal that is to be achieved by using wearable technology is an increase in efficiency, i.e. a maintenance technician should be able to execute his maintenance tasks in a shorter time, thus reducing the time the aircraft has to wait at the gate for maintenance to complete.

In order to gain knowledge on the maintenance process, nine interviews have been conducted with aircraft maintenance personnel from August to October in

2003. The user-centered design process used in this project is described in detail in [1]. The interviews have resulted in a number of preliminary findings:

- As passengers cannot be present during maintenance tasks, the time used for the maintenance task is prolonging the time the aircraft waits at the gate.
- Maintenance personnel needs up-to-date information on the maintenance task.
- Maintenance crews work for different airline companies using different aircrafts.
- Maintenance information has to be specific for the individual aircraft, as aircrafts even of the same type have individual modifications, e.g. different equipment depending on the airline.
- Maintenance tasks range from clearly specified simple tasks ("Armrest in seat 16c loose") to unclearly specified problem descriptions ("Noise in the onboard entertainment system").
- Data used for maintenance includes routine maintenance tasks and additional tasks, e.g. problems detected by the cabin crew during aircraft operation and information provided by on-board self-diagnosis systems.
- Maintenance crew members have to have access to technical documentation of the aircraft in order to solve complex problems.
- Maintenance operations have to be documented. This documentation is a valuable source of information for future maintenance tasks.

In order to cope with this high amount of information in an organized way, we decided to use a knowledge management system. Using the problem description and a system model of the aircraft, a number of possible problem causes can be derived that can then be checked by the maintenance crew.

The knowledge management system also records new information that is found during operation and maintenance and becomes an additional valuable result of the maintenance work.

This paper is organized as follows. First, we review related work about wearable and mobile computing within the aircraft industry as well as knowledge management systems. Then, we present our use case together with the functions that the resulting device shall fulfil. In section four, the detailed concept for the various components of the system are explained, including the wearable device, the aircraft infrastructure and the knowledge management system. The next section explains the new maintenance process and the interaction of the various components. The paper concludes with section six.

2 Related Work

The support of working processes with mobile and wearable computing technologies has a long tradition in the context of aircraft manufacturing, maintenance and operation. In the year 1990, Boeing initiated a project to support the technicians in the assembly of wires [2]. An augmented reality (AR) system was planned which should display important information directly into the field of

vision of the technicians to rid them of paper documenation.

The project ARVIKA (see [3] and [4]) which was supported by the german government from 1999-2003 addressed a similar problem. AR technologies were to be researched and realized to support industrial working processes. As a part of the project, the applicability of AR and mobile computing was investigated in the manufacturing of aircrafts at Airbus. Similar to the conclusions at Boeing it was found that AR is an interesting perspective, but that there were still big technical problems, which could only be addressed rudimentarily. On the one hand, head mounted displays (HMD) are not good enough for daily work yet, on the other hand, position tracking can only be achieved with a lot of effort and the problem of registration still remains unsolved. During the evaluation of the ARVIKA prototypes it was found, that the workers preferred the ones which were technically simple. The HMD as a data viewer without position tracking as well as a tablet PC were more accepted by the users than the AR solution.

In another paper it was investigated under which circumstances a wearable computer with HMD was suitable for aircraft inspection (see [5]). Special effort was put to the design of the user interface. It was pointed out, that there is the danger that the users might rely too much on the computer and that they might skip checks, which are not explicitly demanded by the computer program. User interface issues of checklists on wearable computers are also addressed by Boronowsky et al. in [6].

Another field which can be supported by mobile computers is the remote servicing by experts [7]. Westerkamp et. al describe the use of video-conferencing and shared whiteboards for the collaboration of a technician in the aircraft and a remote expert at his desktop computer.

Complementary to the application of wearable and mobile computers is the deployment of a ubiquitous computing infrastructure. Lampe et al. [8] present a concept for a toolbox which keeps track of all tools that are inside. Time is saved, because the current location of a tool can be looked up in a database.

Knowledge management on the other hand is already well researched. Tools like KAON [9] and KnowWork [10] for example show the importance of this field. The Engcon project [11] shows that knowledge management is on the way to industrial use. Most knowledge management systems use so called ontologies [12] to manage knowledge. Ontologies define a vocabulary, which contains words and their relationships among each other. Based on ontologies new facts with the given knowledge are concluded [13]. On top of these ontologies processes and related documents can be managed [14] [15].

3 Aircraft Maintenance Use Case

The objective of the project is to support the technician with the right information at the right time to reduce the overall maintenance process time. Thus the time for the aircraft on ground shall be reduced, saving costs. The specific problems addressed are described in the following use case, composed from the conducted interviews.

A technician entering an aircraft for routine maintenance, has to check and repair all defects reported by the operation crew during the last flight. There are different kinds of information available to support this task.

All defect reports from the last flight are given in the cabin logbook. While the logbook is usually a paper book, it is replaced by a database in modern aircrafts accessible by a display panel at a fixed place. The troubleshooting manual contains standard procedures for a repair task and a maintenance manual gives detailed descriptions on the different parts of the aircraft and their interconnections. The printed manuals aboard the aircraft are rarely used. It is more comfortable for the technician to access electronic manuals through a PC in the hangar and print relevant pages, although loosing time by leaving the aircraft.

Several parts of the aircraft are equipped with self-diagnostic functions. However, this information is rarely used for the assumed use case, mainly because there are no tools to access and analyse this information inside the aircraft.

If the technician encounters a problem not being able to solve with the available documentation, he might remember a colleague with the needed knowledge and ask him for advise by radio or mobile phone. After a defect is repaired, the technician writes a repair report before dealing with the next defect report in the logbook.

In order to support the technician with relevant information and documentation for the current task at hand, we use location based information retrieval, structual and expert knowledge, which leads to the following functionality:

Logbook and self-diagnosis overview: The device gives its user a list of defects, which have to be addressed in the maintenance session. The list combines two different sources of information: defect reports by the flight attendants in the logbook and automatically recognized errors by a self-diagnosis system. So there is the possibility, that two different entries describe the same defect or that there is a relation between different entries which is not obvious.

For instance, if a transformer is defect, the self diagnostic system generates a defect report. A crew member recognizes that a light in the cabin does not work, so she submits a defect report, too. Without further analysis, two unrelated defect reports would be presented to the technician. In the product structure of the aircraft it is defined, that the light is connected to the defect transformer. Thus, the mobile device will take advantage of the product structure to present an integrated view of the defect reports and to cluster interrelated defects.

Detailed defect report: Defect reports can be examined in detail. Non-functional parts and their locations, symptoms and comments about a defect by the flight attendants can be displayed.

Manuals: Maintenance and troubleshooting manuals can also be accessed with the device. The corresponding sections can directly be activated whenever a part of the aircraft is displayed by the mobile device.

Location list: At relevant locations within the cabin, a list with all parts in the vicinity can be displayed. Thus the location can be used as a filter and

entry point for all information about the aircraft cabin. The technician can easily start an exploration of parts from the location list.

Navigate through aircraft structure: In order to find the necessary documentation in the manuals, the technician can navigate through the aircraft's part structure. So he can access information and documentation about each part within the plane.

Similar defect reports: To access the experience knowledge of colleagues, the device can also search for old defect reports which are similar to a current report. The user can learn from the related repair reports.

Navigate through error classification: The technician can search through the hierarchy of defects in order to find a helpful repair report assigned to defects which are structurally close, in relation to the classification.

Expert contact information: If a related repair report does not contain enough information, the user can obtain contact details of the corresponding colleague to ask him for help by phone.

Write repair report: The mobile device can also be used to write a repair report when the problem was resolved. Data from a previously researched report can be transferred to shorten data entry time.

The interviews with potential users of this device showed, that these functions would be very helpful, especially if they could be accessed during the real-world work. Location awareness makes the device even more valuable, because information can be accessed more quickly.

4 Conceptual Realisation

Figure 1 shows a maintenance worker with the location aware, wearable devices. The interviewees expressed concerns, whether a wearable computer with an HMD would be usable for them. PDAs in contrast were much more accepted. Nevertheless, the HMD has the advantage of being always accessible, even when both hands are needed for other tasks. Thus we decided to design a hybrid handheld/head-mounted system based on a PDA platform.

When the PDA is worn on the belt, it is connected to the HMD. A special input device, which is worn around the wrist, facilitates interaction with the PDA and is used for the localization of the user. If the PDA is detached from its holder, it switches from wearable mode to handheld mode. The toolbox of the technician is enhanced by a notebook computer to store experience data and process knowledge management queries. Wireless connections are used where possible, so that the users are not encumbered with wires.

The localization of the user is an explicit task and does not happen automatically. Fixed RFID tags in the cabin, a wearable RFID reader [16] on the wrist of the user and a mapping table between tag identifiers and corresponding aircraft parts are the components of the localization system. It affords several advantages in this use case compared to absolute positioning systems, e.g. ultrasonic [17] or optical[1] systems:

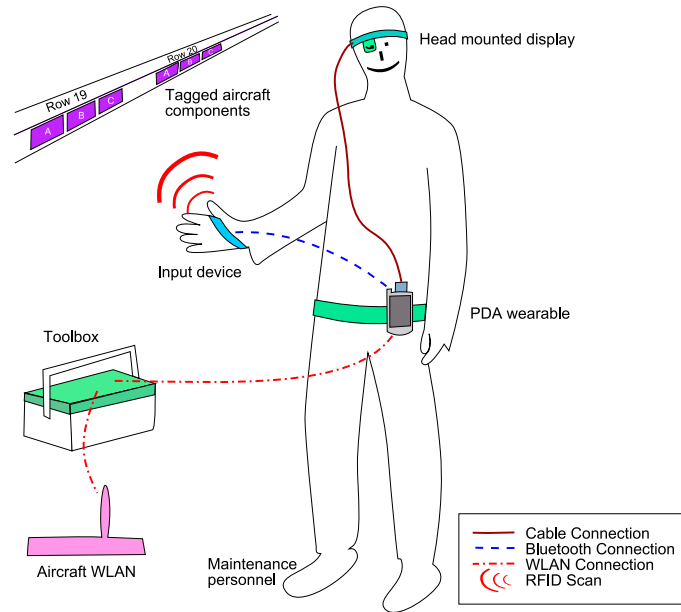[1] E.g. "Precision Position Tracker" by World Viz

Fig. 1. Maintenance personnel with wearable computer

Movement monitoring: the interviewees expressed the concern, that the constant monitoring of their movement in the aircraft could be abused by employers. An explicit system gives them more control over the disclosed data.

Adaptable precision: the requirements on the precision of the localization system are varying. While some areas are of little interest, others are densely covered with points of interest. RFID tags can selectively be attached to interesting areas and can also be selectively identified by the users.

Spatial extensibility: the covered area can easily be extended by adding new RFID tags to the system.

4.1 Aircraft Infrastructure

The mobile devices of this application require a specialized infrastructure to support them in the aircraft consisting of hardware as well as software components. The following components are taken as prerequisites:

Electronic cabin logbook: the paper logbook is replaced by a database which is stored on a server on board the aircraft. The electronic logbook is accessible through an RPC (remote procedure call) interface.

Electronic self-diagnosis system: the logbook is complemented by a self diagnosis system. Several components in the aircraft are attached to this system and produce diagnosis messages also accessible by RPC.

Fig. 2. PDA-Wearable for aircraft maintenance

WLAN: wireless network access is also available within the cabin. The logbook and self-diagnosis system are both connected to the network.

The maintenance application needs additional infrastructure which is developed and installed as part of this project:

RFID tags: passive RFID tags will be installed in the cabin to identify areas. Depending on the size of the cabin, i.e. the number of seats, lavatories, galleys and doors, a varying number of tags will be installed. For a large aircraft, approximately 500 tags are needed. Each seat area will be identified with one tag, different areas of the lavatories, galleys and doors will be marked with six or seven tags.

Part information: a server on board will store information about all parts in the cabin. It includes structural information about connections to other parts as well as a mapping to the RFID tags.

Manuals: aircraft maintenance and troubleshooting manuals will also be installed on the above server. Links between the manuals and the part information enables easy information access.

4.2 Wearable Hardware

An iPAQ H5550 PDA is the basis of the wearable computer for the maintenance worker. It features integrated Bluetooth and WLAN interfaces as well as a 400 MHz Xscale processor and 128 MB of RAM. An expansion pack affords a PCM-CIA slot and an additional battery. A MicroOptical SV-6 HMD can be attached

to the iPAQ by a PCMCIA VGA card[2] which fits into the expansion pack.

The expansion pack with the VGA card will be attached firmly to a belt or shoulder belt. Thus the user can choose how to use it in different situations—as a wearable or a handheld device. When primarily entering information, he might prefer to take the PDA out of the holder to input data with the pen. For text input, this is the only possibility. The preliminary interviews indicate that text input by pen is more accepted by the user group than a one-handed keyboard, e.g. the Twiddler. We abandoned the option of text input with such a keyboard, since free text input is rarely necessary in the use case.

While the worker is engaged in a maintenance task, he might prefer to put the PDA into its holder on the belt. Then his hands are free for the maintenance task and he can view information about the task in the HMD at the same time. While the hardware components so far are commercially available, a customized input device for the wearable mode is needed. The device shall be wrist-mounted, so that the user's hand is free. It will include a small RFID scanner[3], so that the user can simply point to a RFID tag on a part of the cabin to run a location-based query for information. Additionally, the device will include basic elements for navigation. This might be accomplished by a tilt-sensor (compare to [6]) measuring the rotation of the user's hand to select an entry. Another possibility is the use of a few buttons or a wheel (compare to [18]) for navigation. It is planned to build several different input devices and to evaluate them in a users' workshop while the project advances. The device will be equipped with a Bluetooth interface to connect it wirelessly to the PDA.

4.3 Wearable User Interface

One of the challenges of wearable user interfaces is their usability. The possibilities to map user activities to application control is very limited compared to other mobile or stationary devices. Unlike with stationary computing, wearable computing applications cannot assume the existence of full-sized keyboards, high-resolution displays, pointing devices etc. during operation. Therefore, wearable user interfaces should be designed independently from traditional in- and output devices. This independency then allows the application to be adaptable to different device configurations. Beside a device independent design, the use of wearable in- and output devices requires operation concepts beyond the desktop "point and click" paradigm [19]. Suppose for example a simple paddle with a single button as input device for an application. It is obvious that an application with many buttons and windows is not appropriate. But if the application consists only of a single selection list at a time as shown in figure 3(b) a comfortable and easy interaction can be realized.

In the given use case the wearable is used similar to a web browser. It represents the frontend interface to control the backend application by using a graphical user interface displayed on the HMD. However, in the use case the wearable

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[2] We use the HP VGA Out F1252A card.

[3] E.g. MR-1000 from Cavitec (http://www.cavitec.de)
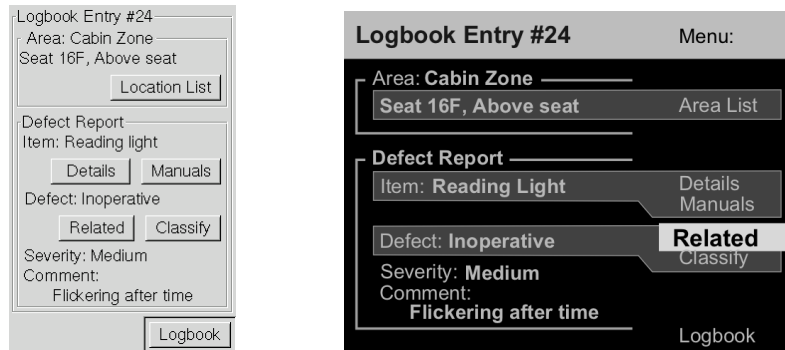
(a) Handheld mode (PDA)

(b) Wearable mode (HMD): the menu on the right can be navigated with a wrist-worn input device. Currently, "Related defects" is in focus of the selection.

Fig. 3. Screenshots of PDA and HMD for the same logbook entry (drafts)

computer core (PDA) can also be used in handheld mode by displaying the user interface on its build-in touchscreen. Because of the different interaction and presentation capabilities of a HMD and a PDA's touchscreen, the user interface must seamlessly adapt its appearance and control mechanism to the current execution context of the application. Basically, there are only two different execution contexts to distinguish, which are "*wearable mode*" and "*handheld mode*". The validity of a context is determined by checking if the PDA is in the holder. Figure 3 shows screenshots of the user interface for the different contexts.

4.4 Knowledge Model

Within the aircraft we have two kinds of models. First, there is a classification of parts, which is called the product model. The second model contains the particular parts and their relationships among each other. This is called the product structure. These two models can be combined to a complex ontology describing the whole plane (see figure 4). Each part of the aircraft is an instance of a concept, which is defined within the classification. Each concept can be set into a relationship to one or more documents. Each part is associated with a RFID tag to specify the area where the part is located.

These models are stored on a server running within the plane. It can be used by the knowledge management system running on the technicians toolbox computer. Defect reports, repair reports and documentation manuals are stored within a text retrieval system with the capability of similarity search. Furthermore this textual information is stored within an ontology, used by the knowledge
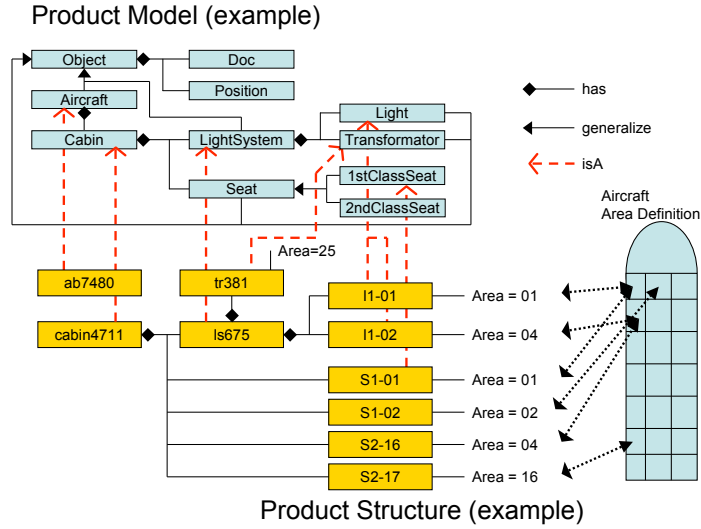
Product Model (example)

Fig. 4. Aircraft ontology (example)

management system in order to relate repair reports to specific defects. Defect reports comprise information about parts, observed symptoms, the date, the airplane, the flight number and other information. A repair report contains information about the solution and the technician, who solved the problem. With the similarity search capabilities in combination with the knowledge management system, it is possible to classify all defects in a defect ontology, which can be established within the knowledge management system [20] (see figure 5). Defect reports can be enriched with information about the defect component. The knowledge management system also supports synchronization to other systems. The entries from the electronic logbook are synchronized with the knowledge base that the technician uses within the aircraft. If the technician enters the aircraft, all messages are copied to his notebook, which is installed in the toolbox. Before entering an aircraft, the whole knowledge of the ground station is synchronized with the technicians notebook. After the technician returns to the ground station, the new knowledge is copied to the ground station's server. Furthermore, it is possible to exchange knowledge with other ground stations all over the world.
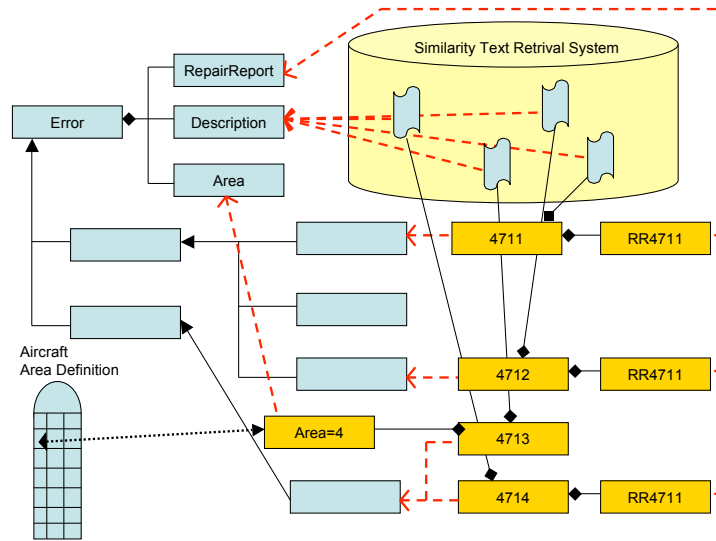
Fig. 5. Defect Ontology

5 New Maintenance Process with Wearable Computer

The new devices change the way how the maintenance personnel accesses information to support the maintenance task. The following use case shows how the different parts of the concept work together.

In the ground station, the technician puts on the belt and the HMD and puts the PDA into the holder. He takes all knowledge of his company with him in the toolbox computer. When the technician enters the aircraft, the toolbox computer connects to the WLAN of the aircraft and downloads the logbook entries of the last flight to the knowledge base. The knowledge management system in the toolbox communicates with the PDA the technician uses to access all needed information. The wearable automatically displays an overview of the reported defects in the HMD. The system utilizes the product structure in order to recognize, whether two or more defect reports describe related errors or even the same error. The closer two defect parts are in the product structure, the more likely it is that the two defects are interrelated. Thus, defect reports are grouped according to these indications, which can save the technician a lot of time.

He walks to the area of the defect and identifies the area with his scanner. Then the wearable displays the detailed defect report. Furthermore, he uses the wrist mounted input device to retrieve information about each component, which can be found in the actual area, with a link to specific documentation. The compo-

nents located inside an area can be concluded from the product structure data. He also explores the product structure. If he needs information about other aircraft parts, he can simply scan the corresponding area to jump to other sections. Eventually, he takes the PDA out of the holder. The user interface vanishes from the HMD and adapts to the screen of the PDA. He continues to browse the documentation and might share the information with a colleague.

With the knowledge management system the technician also has direct access to former repair reports and can take advantage of former expert knowledge directly. Because of the possibillity of a similarity search, the technician can search for equal or similar defect reports. If the retrieved repair reports do not answer his questions, he can retrieve the contact details of the person who filed a specific report before. If he cannot find an equal or similar error, the technician has the possibility:

- to search for less similar errors. In this case, the chance that a repair report is useless is increasing, but it can help to find experienced persons, too.
- to classify the defect. If a defect is classified, the technician can use the defect hierarchy to explore defects, which are in the vicinity[4] of the classified defect. From the found defects the technician can access all information mentioned above.

When the technician has gathered enough information, he starts the repair task. Therefore he puts the PDA back into the holder to have both hands free. However, he can still view the researched information in the HMD during the repair task. With the input device on his wrist he can quickly switch to other parts of the documentation. After repairing a defect he fills out a repair report. If repaired as explained in a former repair report, he can simply transfer that report. On return at the ground station, the new defect reports as well as the according repair reports are added to the ground station server. Furthermore it is possible to share the new knowledge with other ground stations all over the world.

6   Conclusion and Future Work

In this paper we have shown, how the combination of mobile computing and knowledge management offers the possibillity to optimize the maintenance process of an aircraft. There are several different sources of information a technician accesses during the maintenance task, but there is no unified tool to support it. Thus, a concept for a location-aware, wearable information system was elaborated to facilitate this access.

A wearable computer will support maintenance personnel by information on recent defects of the aircraft taken from an electronic logbook and a self-diagnosis system. Manuals and part descriptions relative to the user's current focus of attention become accessible. Knowledge management will enable access to experience knowledge of colleagues and provide structural navigation.

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[4] The distance of nodes is specified by the number of nodes between them.

The core of the wearable computer is a PDA. The device can be used like a usual PDA in the handheld mode or it can be stored in a holder for wearable operation. In the holder, the PDA connects to an HMD and automatically adapts its user interface to the changed modalities. By a wrist worn input device the user controls the wearable. The input device also contains a RFID scanner. The scanner will be used to identify areas in the aircraft. Subsequently the computer can display information and logbook entries associated to that area. The aircraft itself will be equipped with RFID tags and a server to store the part descriptions with references to the RFID tags. Data storage and knowledge management is not possible on the PDA directly. Thus, the PDA is designed as a client to a notebook computer carried in the toolbox of the technician.

The next steps in the project will be the detailed implementation of the various software components. The appropriate input device has to be identified among several variants evaluated in a workshop with users. The best placement of the RFID tags on aircraft parts will also be determined in that workshop. After the implementation the acceptance of the wearable computer by the target user group will be evaluated. We expect to obtain a good understanding of how the device will be used. Since it offers a handheld and wearable mode, the preferred mode for different situations can be identified.

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