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ORIGINAL ARTICLE

# A web and mobile device architecture for mobile e-maintenance

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**Abstract** The paper presents the development of a mobile maintenance support system based on web and mobile device technologies, i.e., personal digital assistant. The architecture relies on a shop floor system and a supporting system in a diagnostic center. The shop floor system is supported by a mobile device, which helps the maintenance engineer to perform maintenance tasks. This gives great support to the maintenance engineer as it facilitates the access to decision-making support, work order, and spare part handling modules etc. that are available in the device. The diagnostic center provides the maintenance engineer with decision support for his various tasks, when needed. Moreover, a database table listener agent, located at the database server, was developed to keep track of the maintenance engineer's work orders at a certain priority level. The proposed approach can reduce the maintenance costs and solve the problem of the unavailability of an expert. More efficient maintenance is believed to be achieved through the use of web and agent technologies since data, maintenance systems, and processing can be gathered and integrated and data can be acquired from additional sources when necessary. The proposed system, the web, and embedded technologies as well as remote communication were tested successfully.

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**Keywords** Maintenance · Condition-based maintenance · Computerized maintenance management system · Decision support system · Web technologies · PDA

## 1 Introduction

E-maintenance is a sub-discipline of e-manufacturing and e-business for the support of the next generation manufacturing practices [1]. According to the author, e-maintenance is "the ability to monitor plant floor assets, link the production and maintenance operation systems, collect feedbacks from remote customer sites, and integrate its upper level enterprise applications". A more general definition is "a maintenance management concept whereby assets are monitored and managed over the Internet". This development is thus the cause of the advances of the new technologies, like the Internet, web, and wireless technologies. Iung [1] believes that it illustrates a revolutionary change rather than an evolutionary advancement. The most preferred maintenance strategy is condition-based maintenance. It is based on condition monitoring and involves the data acquisition as well as processing, analyzing, interpreting, and extracting information from it. The maintenance personnel then identify any deviation from predetermined values. Normally, this is followed by a diagnosis to determine the causes of the deviation. Finally, a decision is taken to determine when and what maintenance tasks are to be performed. The prognosis is made to anticipate a failure as early as possible and be able to plan the maintenance task in advance [2].

The decision support systems that have been used by maintenance personnel to address this issue have changed with time. In the 1980s expert systems and in the 1990s neural network and fuzzy logic were used in condition monitoring [3, 4]. Distributed artificial intelligence has also been used with the advent of the Internet in the late 1990s [5–8]. In this process web technology and agent technology have recently started to appear. The first review of the subject appeared in 2006 [9] and an updated and extended version in 2009 [10]. These technologies obtained a wider acceptance because of the agents' capability to operate on distributed open environments like the Internet or corporate intranet and to access heterogeneous and geographically distributed databases and information sources [11, 12]. Recently a combination of web technology and wireless communication has emerged as an alternative for providing maintenance personnel with the right information on time, wherever it is needed for maintenance analysis and its various tasks.

Piggin and Brandt [13] give an overview of the applications of wireless technology and also things to consider when implementing wireless internet for industrial application. Industrial applications of these technologies are few and even less in condition monitoring and maintenance. Yao et al. [14] made successful attempt to use personal digital assistant (PDA) and PC-based platforms to control and monitor a programmable logic controller (PLC)-controlled manufacturing system, namely, a drill machine. Wang et al. [15] report a remote fault diagnostic system using Internet and mobile devices.

This paper proposes web and mobile device architecture for maintenance and condition monitoring purposes. In this work different user interface designs based on web technology were tested for a computerized maintenance management system (CMMS) and a decision support system (DSS). In the present work, the main client machine was a mobile device, i.e., personal digital assistant, the results of which turned out to be successful.

## 2 The multitier architecture

The proposed Web and Mobile architecture is shown in Fig. 1. It is based on web services and is a three-tier architecture, also referred as multitier, n-architecture, or enhanced client/server architectures [16].

In Fig. 1, M stands for the rotating machines. At the bottom is the three-tier Web and Mobile architecture system. The first tier comprises a couple of databases and could also consist of several database servers. Each database has its own knowledge base. The database stores the data entering into the system. The knowledge base contains procedures, rules, logic steps etc. for processing a specific problem or work task. The middle tier consists of the application Web services and Web server. Finally, the third tier is where the user interacts with the system through the client machines, i.e., computers and mobile devices. The shop floor personnel can communicate/collaborate with the expert/s at the diagnostic center when need be.

The first tier consists of databases which are characterized by various factors such as their ability to provide long-term reliable data storage, multi-user access, concurrency control, query, recovery, and security capabilities. In maintenance these are important factors because of the need of, for example, gathering and storing data for the purpose of monitoring machine health. Du and Wolfe [17] review the database technologies. The review goes through the database architectures such as relational databases, semantic data modelling, distributed database systems, object-oriented databases, and active databases. They mention that the architecture most used is the relational database architecture. It has high performance when simple data requirements are involved and has been widely accepted. However, other database architectures may be needed for complex data. MIMOSA, for example, has developed a common relational information schema (CRIS) (www.mimosa.org). It is a relational database model for different data types that need to be processed in CBM application. The databases chosen can be centralized or distributed [16, 18, 19]. The centralized systems are the oldest type. One of the advantages is that the complexity is reduced, since the networking and application development processes are both affected by the minimal distribution of computing. Moore and Starr [20] also mention that centralized databases are fraught with difficulties as well, since their size may make them difficult to manage. In other words, they are not practical and require complex hardware and software to operate effectively. Because of the complexity of the system the setup cost can be very high. Moreover, the operational and maintenance costs can escalate. Normally, the failure of a system may affect a great many sub-systems. Backup management can be both time-consuming and expensive. B'Far [19] mentions that since in the centralized systems the entire application is in one place, their inflexibility makes them unpractical. Moreover, any type of customization to the application has scalability difficulties and maintenance becomes complicated since the entire application is in one place as one piece of software. It was also realized that by breaking up applications into pieces the cost and complexity of modifying applications could be reduced. Various business conditions also encourage the use of distributed databases and systems [16] for reasons of distribution and autonomy of business units, data sharing, data communication costs and reliability, multiple vendor environments, database recovery, as well as transaction and analytical processing. Moreover, the advances in multitier architectures, database management systems and web technologies favor the use of distributed database systems.

The second tier, also normally called middleware, is the software technology. It emerged during the middle of the 1990s and is the cause of the developments in network

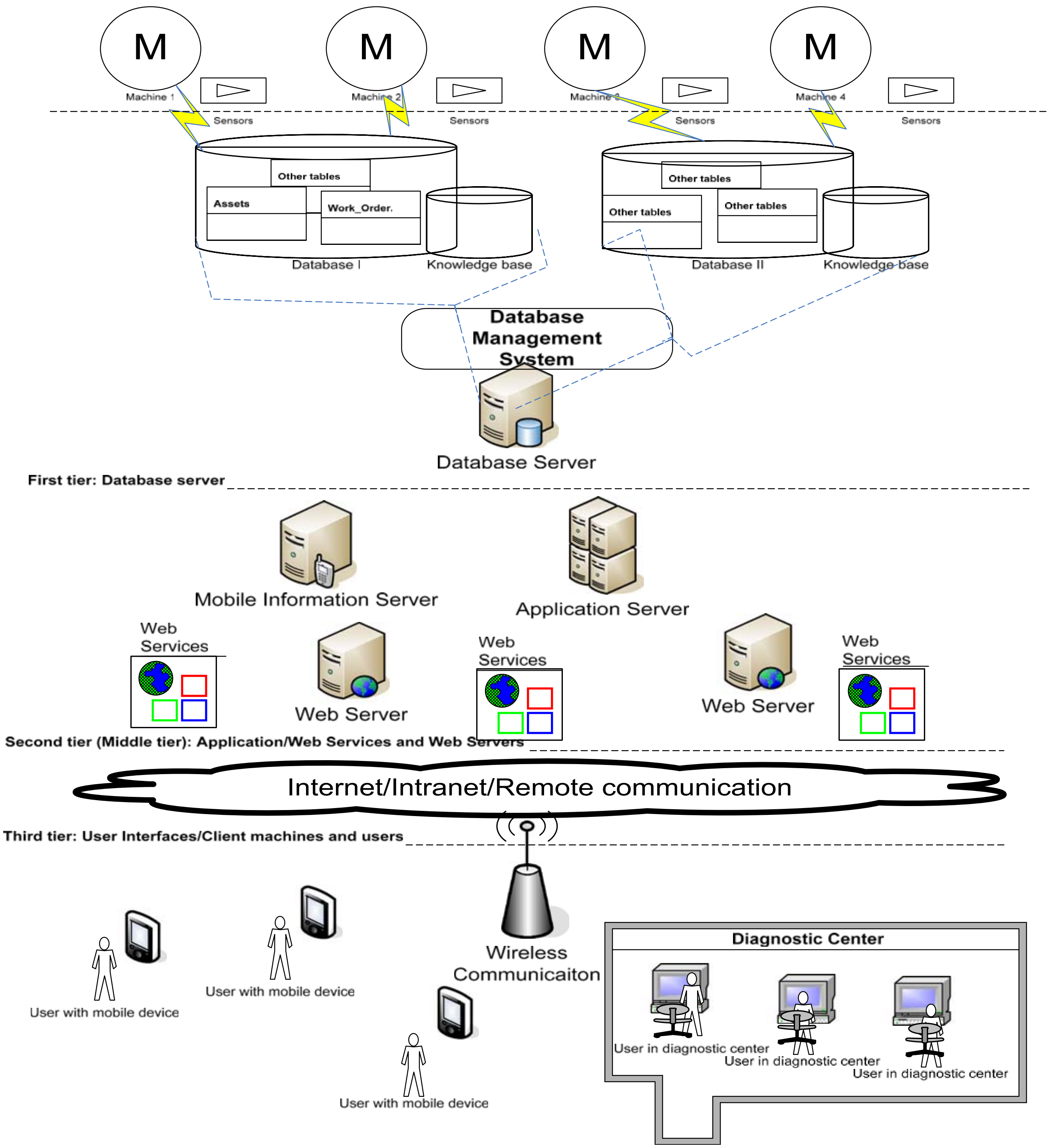


**Fig. 1** The web and mobile architecture

technologies. They facilitate the development of multi-dimensional applications [21] as well as the interoperability between other software applications. The web services (WS) are characterized as middleware since they are also the application software that is designed to support interoperability among the applications distributed across a network (World Wide Web Consortium (W3C), www.w3.org). By WS, the conveying of messages from and to the client machines is facilitated. The potential of web services is that they can be consumed via the Web to any application program independently of the language used. They consist of three basic components [22–25]. The first component is XML. It is a language that is used across the various layers in the web services. The second is the SOAP listener. It works with packaging, sending, and receiving messages over the HTTP. The third component is the web services description language (WSDL), the code that the client machine uses to read the messages it receives. WS development can take place with the help of many programming languages from many vendors like Java Sun or Microsoft. Another important component in the WS is the repository for universal description, discovery, and integration (UDDI) protocol. The UDDI produces a standard platform that the WS can use, providing various applications to find access and consume the WS over the internet (www.uddi.org).

The MIMOSA Open system architecture–enterprise application integration (OSA-EAI) services were considered during the development process (www.mimosa.org). Their use enforces standardization and at the same time follows the general idea of a web service, i.e., that the processing and handling of the web methods can be different, but the input and the output of data use the same data types without worrying about differences in the user interfaces. For this, the WS and web methods need to be standardized, i.e., the web method names return types, and input parameters. They enforce a standard calling convention for each web method. The result is that various users can call the web methods in the different kinds of WS that have been developed without worrying about differences in the interface.

Moreover, the use of WS increases the benefits of the EAI by means of standardizing the application interfaces [26]. This goes in hand with the latest development of the service-oriented architecture (SOA). The SOA has emerged as the service middleware technology of the future in the telecommunication environment [27]. It is based on WS and highlights the various business processes in an organization through the development of the WS [28]. In addition, through the commonly accepted standards of WS, web methods etc. are the interoperability, shareability, and reusability ensured in an organization.

The third tier, also called presentation tier, consists of the client machines. It can be a desktop or laptop. However, recent years have seen a wide variety of computer devices including mobile telephones, personal digital assistants, and pocket PCs has been introduced as an alternative to traditional computers [29]. The devices have normally technological variety and a diversity of users who differ in skill and knowledge. There are also studies showing that the personalization of the user interface, i.e., the multiple choices of user interfaces depending on the specific user, can make a difference when it comes to factors such as friendliness and efficiency [30].

## 3 Development of the system

The system developed uses three information and communication technologies (ICT): web services, web servers, and remote access for communication between the database servers and client machines. The database server in the tier

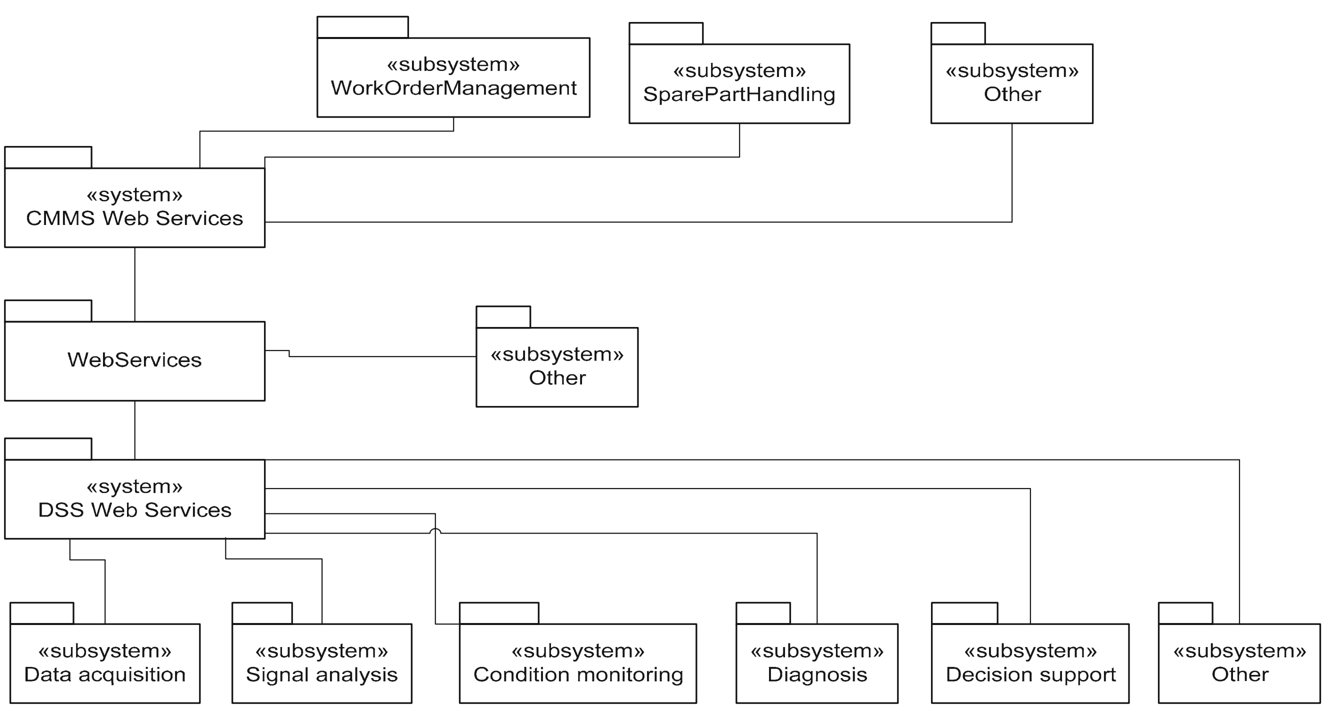


**Fig. 2** The CMMS and DSS web services

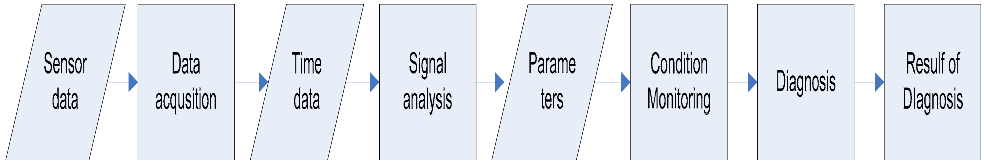


**Fig. 3** The data flow and its various processes

architecture system can also be directly and remotely accessed by mobile devices through wireless communication. Several communication protocols with diverse characteristics can be used for the wireless communication between the client machines and the objects in the system.

Figure 2 shows the unified modelling language (UML), a component model. The developed software is composed of two systems: the web-based CMMS and the web-based DSS. Both of the systems consist of web service technology. It also shows the software architecture and the relationship between the packages. At the top of the figure is the CMMS, which in this case consists of two subsystems (work order management and spare part handling), and below it is the DSS. This consists of five sub-systems: data acquisition, signal analysis, condition monitoring, diagnosis, and decision support. “Other” in the figure means other systems or sub-systems that can be added to the application software.

### 3.1 The decision support system

The web-based DSS was tested with a simulated signal from a fault rolling element bearing. The data flow and the various processes involved are illustrated in Fig. 3. While doing so, OSA-CBM, the MIMOSA CRIS data structure, MIMOSA OSA-EAI Services, and ISO 17359 standards were taken into consideration.

It is in the application program (software) where the data processing takes place. This lay normally in the middle layer when web applications are used. There lays the knowledge and business rules from the application domain. These rules provide decision making support and prognostics possibilities. The rules normally use techniques based on statistical, artificial intelligence, and model-based approaches.

Jardine et al. [31] reviewed recent research and development in diagnosis and prognostics of mechanical systems implementing CBM with emphasis on models, algorithms, and technologies for data processing and maintenance decision-making, while Campos [10] goes through the available literature on the application of information and communication technologies, more specifically, web and agent technologies in condition monitoring and maintenance of mechanical and electrical systems. However, the examples of this application are based on the data processing of time domain and spectrum data.

In Fig. 3, the sensor data comes from different sensors in the machine and is then stored in the data acquisition layer of the database. From there the relevant time data moves to the next layer, the signal analysis layer. The results of the signal analysis in the parameter chosen are compared with the condition-monitoring reference values in the condition-monitoring layer. Finally, a diagnosis is made and a decision is taken. Next the diagnosis values are displayed. Outputs from the mobile device emulator’s window from the web and mobile architecture are shown in Figs. 4 and 5. In Fig. 4 the time domain signal is shown. It is the RMS value of the vibration velocity expressed in mm/s. The frequency spectrum of the same signal is shown in Fig. 5.

### 3.2 The computerized maintenance management system

According to Zhang et al. [32], the use of a well-implemented CMMS can lead to increased quality, improved decision-making, and increasing efficiency. In a traditional system, the shop floor personnel usually insert into the CMMS the information in a few words written on a notepad, agenda, or at the back of a maintenance work order [32, 33]. This consequently leads to low data quality and poor registering of the situation resulting in information that does not add any value to the background of the history of the equipment. The proposed web-based CMMS, i.e., the work management system, allows two forms of work order generation. The first form is generated automatically on the basis of scheduling or when the alarm level crosses some pre-determined level in the time or frequency domain. However, all the “red lights” should be on before a high-priority work order goes to the maintenance engineer. This is done so as to avoid unnecessary alarm signals and stoppages. Moreover, normally the generated work orders are of the “yellow light” warning level, i.e., the maintenance engineer is asked to check the bearing because there may be some signal here indicating that something could be wrong. This is done in the system through the specification of the priority level of the work order. The second way to generate a work order takes place at the shop floor if the maintenance engineer sees that something should be done to the equipment. The engineer then sends a work order which is registered by the system and forwarded with a priority level by the system to the maintenance engineer who has the adequate knowledge. Figure 6 shows how the

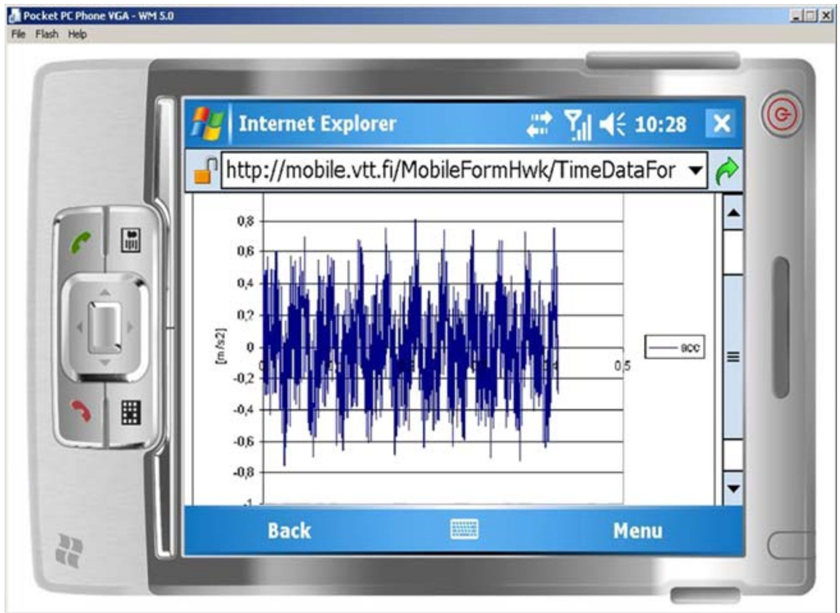


**Fig. 4** Simulated vibration signal in time domain

asset event and fault description are created through the mobile device.

In the work management system, an intelligent agent, i.e., a database table listener agent (DBTLA), was developed. According to Turban et al. [18], intelligent agents are small software programs that exist in computers to conduct certain tasks automatically. They run in the background, monitor the environment, and react to certain trigger levels. Wooldridge and Jennings [34] define intelligent agents, or simply agents, as a software with operational attributes like autonomy (each agent's ability to act without human interaction), social ability (the ability to interact and cooperate with other agents and the user for data and information exchange), reactivity (their ability to perceive the changes in their environment and to respond to these changes), and pro-activeness (acting as expected to achieve a common goal). However, the purpose of the DBTLA was to monitor certain values inserted into a table. In the case of a work order being generated with a specific priority level, the DBTLA sends in real time a notification to the maintenance engineer who can see this on the user interface. The user's attention is drawn to the notification on the user interface by a twinkle light on it. It is also possible to give notification about the work order by sending a short message service to the PDA. The notification is connected to the work order, which

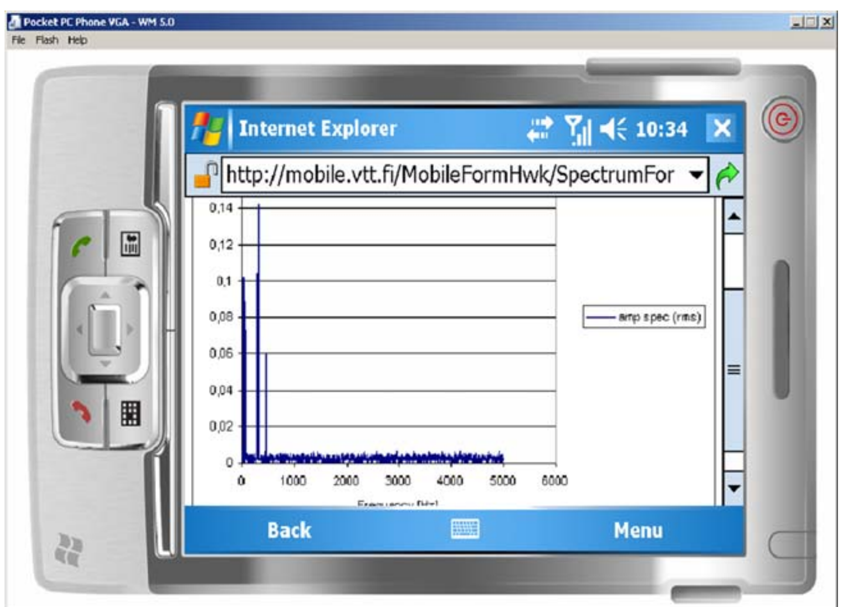


**Fig. 5** Frequency spectrum of the time domain signal in Fig. 4

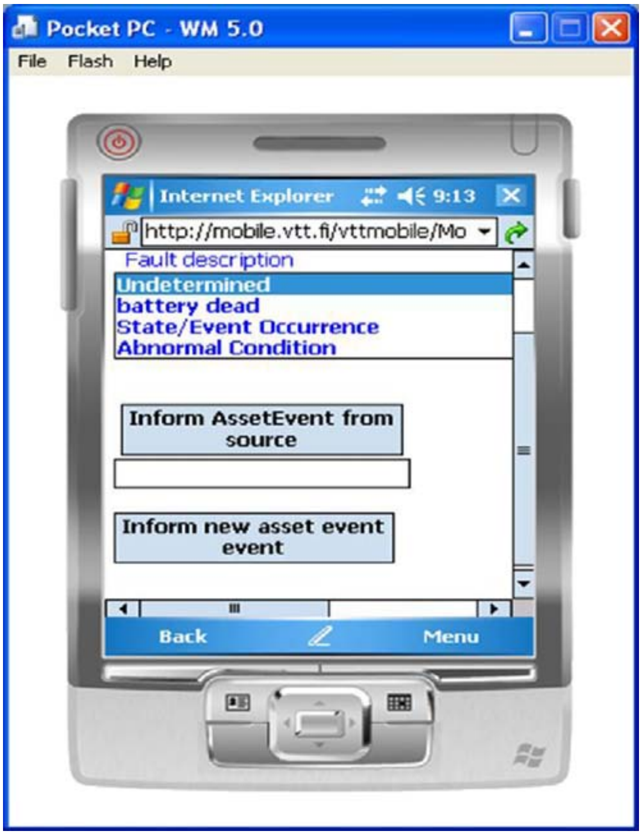


**Fig. 6** Asset event and fault description created

specifies when the work order should be started and finished, its name and work order ID, etc. The rows that the DBTLA monitors form the priority level at the work order table. In cases when the work order does not pass the warning limit, it is put in the queue on the basis of its priority level.

The system should also be able to provide information to the maintenance engineer about the state of the spare parts for the specific work order. If the work order needs some spare parts and the system notices that those are not in the store, an order is sent to buy them.

### 3.3 Work management user interfaces

The user interface comprises the hardware and software that facilitate communication and interaction between the user and the computer/system [35]. There are many types of interface modes (styles) in traditional client machines. These are menu-driven interaction, pull-down menus, command language, questions and answers, form interaction, natural language, graphical user interface, hybrid modes etc.

In recent years a wide variety of computer devices such as mobile telephones, personal digital assistants, and pocket PCs have been introduced [29]. These devices have a variety of users who differ in their skill and knowledge. According to Hilbert and Trevor [30], studies have shown that the personalization of the user interface, i.e., the multiple choices of user interfaces that depend on the specific user, can make a difference when it comes to factors such as friendliness and efficiency. Nevertheless, in this work two mobile device user interfaces were tested for the work management system. Figure 7 shows the first user interface developed with embedded technology. It shows that it has three different buttons with different colors: green, yellow, and red. The second user interface developed was based on a web application and its buttons were of the same colour (Fig. 8). However, the interaction (connection) with the database server takes place through web technology, i.e., web services for both the Web and the embedded technology user interface.

The alternatives for interaction with the system are the same, however. Table 1 shows the alternatives that the user has to choose among when clicking a button for interaction with the system.

The user interface and the system were tested through the use of various scenarios. In one of the scenarios the interaction starts when the work order is generated automatically by the system or by the maintenance engineer. This is illustrated in Fig. 9. The work order sends

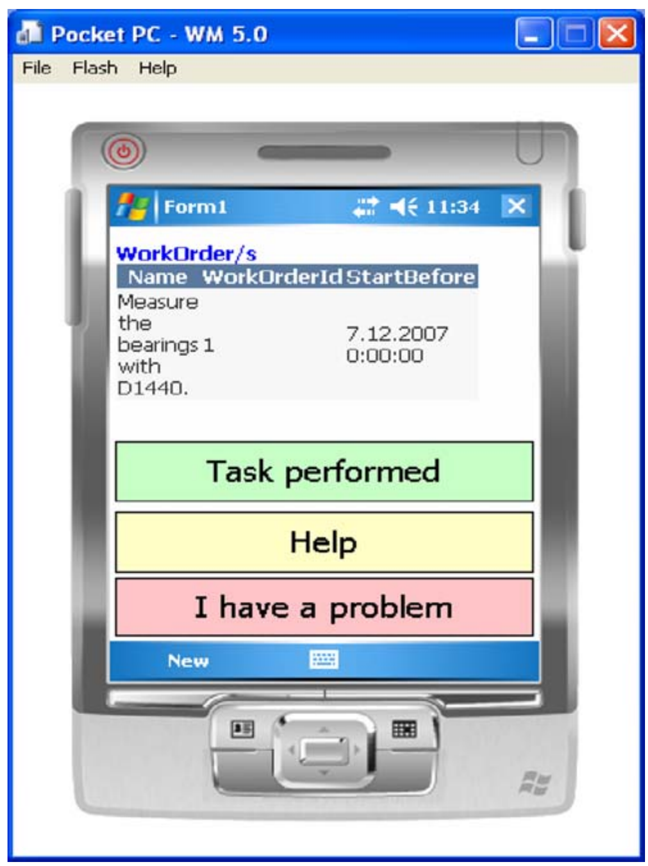


**Fig. 7** Work order window with interactive user interface, embedded technology


**Fig. 8** Work order window with interactive user interface, web application

a request to the maintenance personnel to measure the bearings with D1440. The maintenance engineer has then to decide if this work order can be taken and answered appropriately according to the alternatives available in the PDA. In this case the answer is "Yes/Ok". The following step of the task is "Get D1440" and after doing that the maintenance engineer replies "Task performed". The interaction continues until the task has been finished and all the steps for the work order are fulfilled. When this is done, the maintenance engineer gets the next-in-turn work order.

The second user interface tested provides the maintenance engineer with an overview of the various steps (Fig. 10). This user interface is more traditional since the user is given the possibility to browse from one window to another. It shows the same work order as the one illustrated earlier. Independent of the work order, the information sent to the maintenance engineer is the same, i.e., the work order ID, issued date, 'start before', 'end before', priority level, name, and description. Moreover, the various work order steps can be consulted by the maintenance engineer if necessary. This is done through navigating the links to the specific work order steps window.

Both user interfaces for the CMMS, i.e., work management in Figs. 7 and 9, were tested with successful results. Which user interface is preferable depends largely on the specific user preferences and knowledge. However, how to be successful in the design of mobile user interfaces is an area that is in its infancy, especially within maintenance where there is still a great deal to learn.

A PC solution was also developed to be used at the diagnostic center. It was connected to all the database server data tables based on MIMOSA CRIS. In this way it was easy to administrate, for example, the CMMS, i.e., add, change, update, and delete data and information in parts of the system like work order management.

The proposed system provides maintenance engineers with the possibility to communicate with an expert at the diagnostic center for advice in various work tasks. This results in increased efficiency and productivity in their work. It also increases the quality of the data sent from the maintenance engineer on the shop floor into the CMMS.

Security factors should also be considered when developing applications with ICT—in this case, web and mobile device applications. For this reason, it is also important to develop a security plan based on security issues and threats to the specific applications at hand [36]. The factors that make web and mobile devices more vulnerable are the cases involving the lack of an authentication process and of secure communication [23]. There are ways to decrease these factors with, for example, security policies and encryption. Although security aspects were not considered in the development of this system, they are nevertheless important.

## 4 Conclusions

The emergent information and communication technologies are shown to be important factors to consider for the next generation maintenance, i.e., e-maintenance. They provide the maintenance personnel with possibilities, such as access to the needed information from any geographically located asset at any time and place. They also support the integration of heterogeneous data, systems, and processes. Moreover, the wireless technologies are also advantageous due to the elimination of connecting cables between the monitored equipment and monitoring systems, thus providing a more flexible plant layout.

The proposed system was first developed in an emulator where various requirements were tested. Afterwards those functions were tested on a mobile device, i.e., personal digital

**Table 1** Button alternatives of the PDA user interface

| Green button | Yellow button | Red button |
|---|---|---|
| Task performed | Help/Don't know | I have a problem |
| Yes/Ok | Maybe | No |
| Right | Center | Left |
| High | Medium | Low |

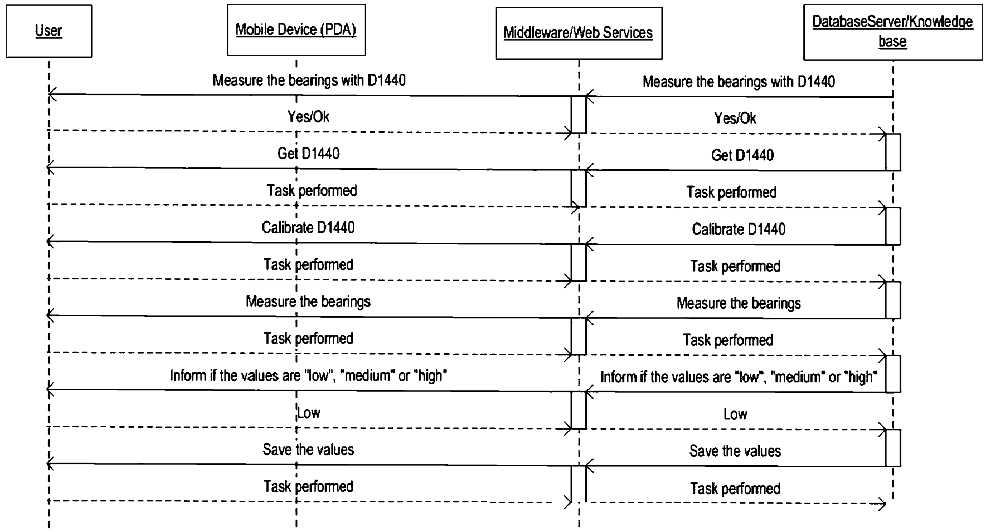


**Fig. 9** Sequence diagram for the interaction between the user having a PDA and the system

assistant. The mobile device could also access the data using web services. It is a useful development as there is normally a huge amount of data needed for diagnosis whereas the storage capacity of a mobile device is small. For this reason, the use of web services and web servers for this part of the system was a good approach to take. Furthermore, with the component-based software and the tier architecture it is easier to reuse, add, or maintain certain functionalities of the system.

The use of web-based decision support system and computerized maintenance management system, i.e., work management modules for the mobile device, provides the shop floor personnel with a tool that can insert data into the system in real time. This increases the quality of the data going from the shop floor into the system. Moreover, the use of mobile devices facilitates the collaboration between the maintenance personnel on the shop floor and an expert sitting at the diagnostic center. This possibility is important in cases where the level of operator knowledge or technical expertise on the plant floor is low. It is believed that the use of the mobile device increases productivity in the various work tasks of the maintenance engineer.

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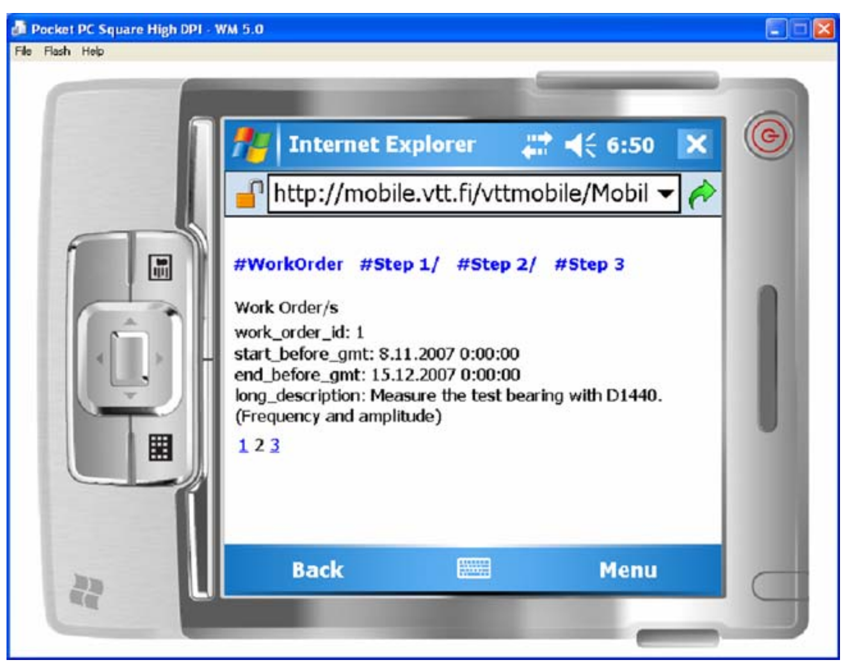


**Fig. 10** Information about the work order and link to the work order steps

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