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ABSTRACT

The paper gives a short overview of the enabling tools and technology available to the maintenance engineer in manufacturing industry, in relation to the emergence of e-maintenance practices and the introduction of mobile computing devices. An analysis of the main characteristics of the e-maintenance concepts and the associated challenges is provided, highlighting the lack of use of condition-based maintenance strategies. The potential of using ubiquitous computing in industrial maintenance practice is then examined, followed by an original vision for the adoption of mobile maintenance management solutions, which can facilitate the implementation of condition-based-maintenance. This vision is supported today by the European Integrated Project DYNAMITE 017498 (Dynamic Decisions in Maintenance).

INTRODUCTION

Today maintenance is going through major changes. The industry and also the public are realising that the efficient use of industrial assets is a key issue in supporting our current standard of living. In this context, efficiency means producing good quality products without interrupting the production for unnecessary breakdowns.

With current ever growing demand for improvements on system productivity, availability and safety, product quality, customer satisfaction and taking into account the trend for decrease in profit margins, the importance of implementing efficient maintenance strategies becomes unquestionable. In this setting the maintenance function plays a critical role in a company's ability to compete on the basis of cost, quality and delivery performance and maintenance is taken into account in production requirements (Al-Najjar & Alsyouf, 2003; Crespo & Gupta, 2006; Pinjal et al., 2005). For example, studies over the last 20 years have indicated that around Europe, the indirect cost of maintenance is equivalent to between 4% and 8% of total sales turnover (similar amount as for the direct cost). Thus, in the countries where modern maintenance practices have yet to be well adopted by industry, the potential savings from modern maintenance are massive. These modern and efficient maintenance practices involve, at least, the identification of the root-cause of component failures, reduction of production systems failures, elimination of costly unscheduled shutdown maintenances, and ultimately an improvement both in productivity as well as in product quality.

At the very end of this changing focus on maintenance there exists a new role for the maintenance function, particularly for the manufacturing industry, taking into account a life-cycle management oriented approach. Here, limits on resources and energy consumption will invoke a sharp change in the objectives of manufacturing, shifting from the need to produce more efficiently, to the need to actually produce new assets as late as possible, while ensuring customer satisfaction and profits. In this manufacturing paradigm shift, a new culture wherein maintenance activities become of equal importance to actual production activities, is becoming highly relevant (Takata et al., 2004).

To support this role, the maintenance concept has undergone through several major developments involving proactive considerations, which require changes in transforming traditional "fail and fix" maintenance practices to "predict and prevent" **e-maintenance** strategies. Such an approach takes into account the potential impact on service to customer, product quality and cost reduction (Lee 2004). The key advantage is that maintenance is performed only when a certain level of equipment deterioration occurs rather than after a specified period of time or usage. In other words, there is a shift away from current mean-time-between failure (MTBF) practices to mean-time-between-degradation (MTBD) technologies. E-Maintenance provides the opportunity for the 3rd generation maintenance and is a sub-concept of e-manufacturing and e-business for supporting next generation manufacturing practices (NGMS).

One key support factor of this 3rd generation maintenance is the concept of mobile devices or mobile agents, offering the flexibility to initiate applications at flexible locations in unstructured networked environments, to quickly and efficiently search for and retrieve relevant information (i.e., on component or equipment degradation) from heterogeneous data sources, to perform tasks and to provide asynchronous services to client requests. For example, personal digital assistants (PDA) devices play a key role in bringing Mobile Maintenance Management closer to the daily practice at the shop floor. The PDAs enable the maintenance personnel to directly gain information from monitored machinery i.e. what is the current state, which maintenance actions have been carried out on them and how future necessary maintenance actions should be carried out.

WHAT IS E-MAINTENANCE?

Baldwin (2004) proposes to define e-maintenance as "The network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed. E-maintenance is a subset of e-manufacturing and e-business". In accordance with the notion of integration and synchronisation, the Intelligent Maintenance Centre defined e-maintenance as "the ability to monitor plant floor assets, link the production and maintenance operations systems, collect feedbacks from remote customer sites, and integrate it to upper level enterprise applications". A more general definition is "maintenance management concept whereby assets are monitored and managed over the Internet". Indeed Internet regarded as a new technology, have led for some companies to replace conventional reactive strategy by proactive vs. aggressive strategies as shown by Swanson (2001).

It is shown by Iung (2003) that in that way, e-maintenance is integrating the principles already implemented by tele-maintenance, which are added to the web-services and collaboration principles. Collaboration allows not only to share and exchange information but also **knowledge** and (e)-**intelligence** (new services**,** new processing). By means of a collaborative environment, pertinent knowledge and intelligence become available and usable to the right place, at the right time, in order to facilitate reaching the best maintenance decisions all along the product life cycle (design, manufacturing, use, end-of life). The distance between actors is now measurable in "network intelligence power" rather than in thousand of miles (Ulieru et al., 2000). Thus, with the use of Internet, web-enabled and wireless communication technology, e-maintenance is transforming manufacturing companies to a business service to support their customers anywhere and anytime.

Leger et al., (1999) point out that some companies (such as General Motors, Canon, Rockwell, etc.) have been investigating e-maintenance for several years now and have already adopted it with significant impact on business process changes. Some e-maintenance platforms such as ENIGMA, TELMA, ICAS, PROTEUS, CASIP … exist, where the resulting e-maintenance infrastructure replaces the conventional hierarchical structure by a heterarchical or intelligent one as advocated by the IMS (Intelligent Manufacturing Systems) worldwide initiative (Yoshikawa 1995). Such an infrastructure is adding "intelligence" to components through Infotronics and extensive use of distributed agent technology (Lee 2004). It entails several networks for supporting not only the exchanges between the enterprise and its external relationships (e.g., CRM) but also real-time communication between devices, machinery and computing equipment at different Enterprise levels (ERP, MES).

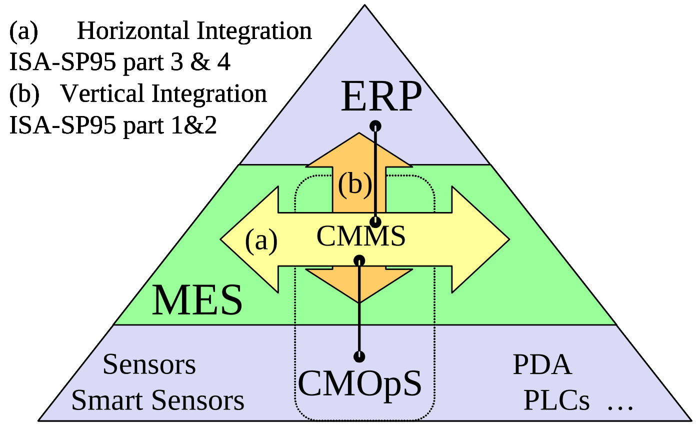
In general, the e-maintenance view supplements the ERP in managing the risk associated with “faulty” performance, and the MES in anticipating (and reacting) as fast as possible to progressing degradation (and failure) of the manufacturing processes. Thus, the maintenance information system (i.e., the computerised maintenance management system (CMMS) and the computerised maintenance operational system CMOpS) is strongly related to the ERP/MES in supporting condition based maintenance (CBM) and predictive maintenance (PdM). Based on this relevance, different layers of the e-maintenance architecture () can be defined (Yu et al., 2003):

- A **maintenance decisional layer** allowing on the one hand the definition of the maintenance policy applied equipment, in accordance with the Enterprise policy, and on the other hand supporting staff management and the purchase management related to spare part. This layer could be considered as **STRATEGIC** level.

- **A maintenance management layer** where the CMMS aims at “deploying” the maintenance policy selected at the decisional level. In collaboration with the manufacturing area, it plans the interventions required to maintain the system and ensures the logistics support. i.e. the resources, services and management means necessary to the maintenance intervention execution. Today, the maintenance functions implemented at this level through CMMS have to be vertically integrated with the ERP solution in accordance with part 1 and 2 of the ANSI/ISA SP95 standard (IEC/ISO62264). This layer could be considered as **TACTICAL** level.

- **A maintenance operational (local) layer** implemented by the integration of the CMMS with all the MES functions (part 3 and 4 of the ANSI/ISA SP95) and by linking the “Computerised Maintenance Operational System” with field tools and field components such as condition monitoring tools, PLCs, sensors and actuators (Léger 2004). The goal of the maintenance function at this level is (a) to check the availability state and degradation status of each component in order to master system performance, (b) to give support and assistance to the operator for degradation vs. failure diagnosis and then for preventive and/or corrective action deployment, and (c) to calculate performance indicators related to system functioning from data provided by field components. Nevertheless, some of these components can already support “basic” maintenance functions in the case of smart components deploying processing capabilities (i.e. instrumentation with field bus interface and internal memory and processing). This layer could be considered as **OPERATIONAL** level.

Figure 1. Maintenance layers within Enterprise organisation.



CHALLENGES IN E-MAINTENANCE

On each of these maintenance layers, various actors (or agents) have been assigned responsibilities for fulfilling the expected Maintenance services. In order to implement these services, the actors have to exchange heterogeneous information, which varies in content, as well as transmission characteristics. Taking into account the geographical spread of these actors in the Enterprise environment (distributed architecture; different hierarchical layers), the information exchanges require communication support, such as office networks dedicated for management-level issues and industrial networks for production and execution-level issues. The main differences between these two types of networks arise at the lower production levels (i.e., field components levels). In that way, wireless technologies may provide considerable savings in networking cost and degree of flexibility not met in wired systems (Egea-Lopez et al., 2005). The choice of the communication (wireless or not) is related to the constraints/benefits it can bring according to the actors features and the relationships between actors required for supporting maintenance application.

Some of these items can be described as follows:

- The degree of **mobility** asked by the actor. A PDA-equipped actor must act at different geographical locations on site and must be able to be connected easily to the field components, necessary to carry out the maintenance work-order. On the other hand, the CMMS can physically reside in the main office (data office), containing the central maintenance-related Data Base (linked to the ERP database).

- The **distance** between actors. A very short distance between actors (intra-layer interactions) facilitates the implementation of wireless technology whereas a long distance between actors (inter-layers interactions; interactions between companies) supports the deployment of traditional wired networks. For Wireless Technology, the distance can lead to develop infrastructure solution rather than ad-hoc solution (or vice versa) (Remondo & Niemegeers, 2003).

- The type of service supported by each actor and thus the information content to be transmitted, taking into account traffic conditions.

- The environment of the actors (i.e. industrial) and the constraints which are applied to them (i.e., safety).

Most of the previous items are materialised in “the Roadmap for Network Technologies and Services” (Alahuhta et al. 2004) by the concept of **Multi-sphere reference model** leading to identify current challenges in e-maintenance.

Collaboration, web-services, e-Intelligence and Infotronics are key enabling factors for an e-maintenance approach, which has well defined scientific foundations and industrial benefits. Indeed, the positive impact of e-maintenance on productivity, sustainability and quality, has to be demonstrated to justify investments in this emerging field. Thus as highlighted by (Iung & Crespo, 2006), future common industrial/academic working/research directions address, but are not limited to:

- Incorporation of new technologies concerning “intelligent devices” such as micro-electromechanical systems (MEMS), mobile computing devices and smart tags, to support remote monitoring and diagnosis and for assessing component performance (i.e., IP project DYNAMITE 017498 and IP project SMMART (Smart, 2005)).

- Modelling and deployment of new services, such as e-monitoring, e-diagnosis, e-prognosis and e-logistics, which require information from “intelligent devices” for helping maintenance decision making according to system expected performances.

- Development of reliable data repositories that can improve the quality of decision making process by statistical analysis of relevant information such as failure models, usage, etc.

- Extension of the e-maintenance services over the whole Product Life Cycle (to track the product from birth to death) (i.e. IMS Project PROMISE (Kiritsis, 2004)).

- Developing theories and tools for describing, quantifying and optimising the behaviour of the interactions of the system-maintenance-economy model (MME) and then developing maintenance decision support systems (MDSS) for cost-effective decisions enhancing company's profitability and competitiveness continuously (Cost-effectiveness models).

- Modelling of interoperability requirements between all the e-maintenance services (and software) and definition of ontologies formalizing the e-maintenance service semantics (i.e. IP project DYNAMITE 017498, project PROTEUS (Bangemann et al., 2006), MIMOSA initiative (Machinery Information Management Open System Alliance) – IEEE 1232, IEC/ISO62264 (Enterprise – Control system Integration) based on ANSI/ISA S95).

- Development of new Infotronics-based e-maintenance systems offering integration of distributed intelligent devices, services and maintenance software such as CMMS. It consist, for example, in proposing new protocols for collaboration and negotiation, DAI techniques, maintenance workflow, maintenance web Services (Venkatraman 2004), maintenance web semantic etc. but also proof tools to verify the properties of the global functioning from each distributed items (i.e., Proof-oriented fault system engineering).

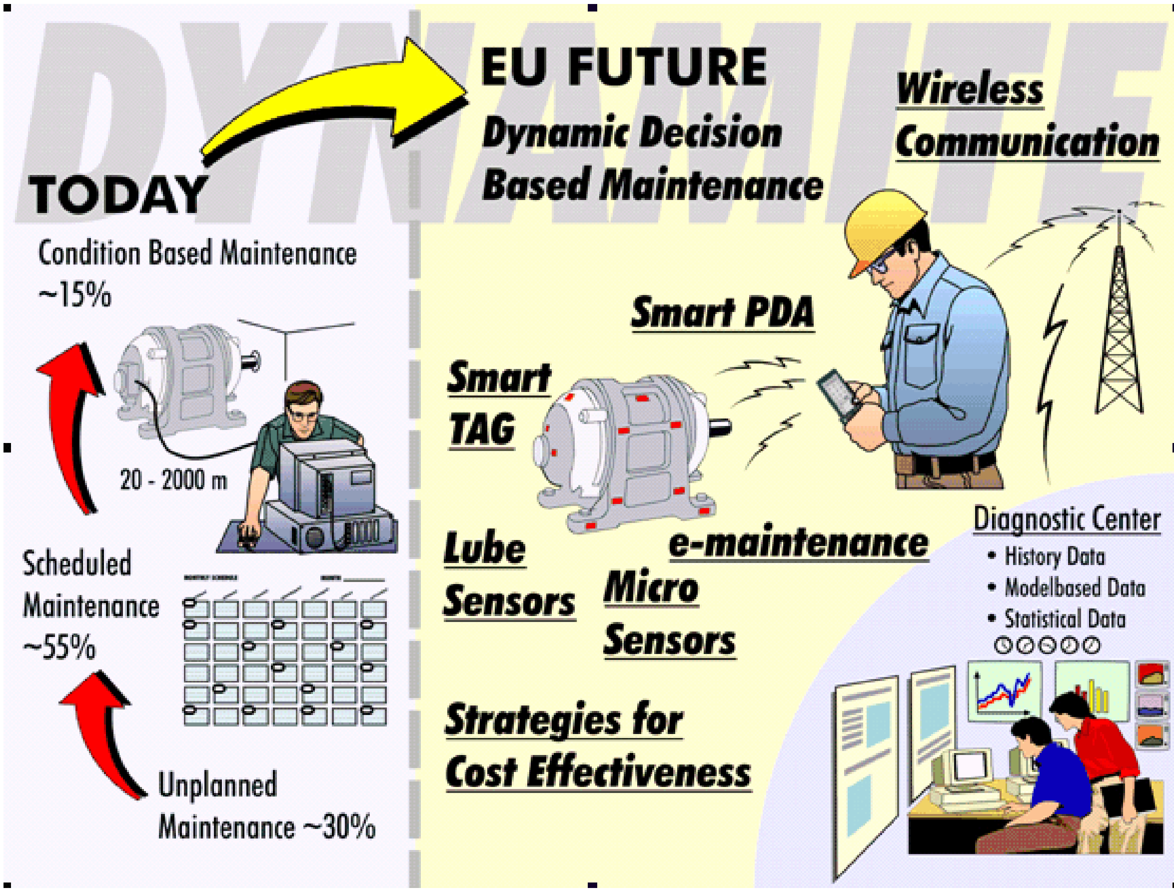
- Adoption and incorporation of industrially relevant standards for wireless networking, wireless ad-hoc sensor networks, and real-time and safety constraints (i.e., IEEE 802.11x, IEEE 802.15.4, EN457:1992- ISO7731).

IP DYNAMITE: FLEXIBILITY AND MOBLITY TO FACE CURRENT E-MAINTENANCE CHALLENGES

Clearly more research effort is required to face up to the challenges for modern e-maintenance. One focused research direction is offered by the new EU-funded Integrated Project DYNAMITE - Dynamic Decisions in Maintenance, coordinated by VTT Technical Research Centre of Finland. It includes six research institutes in the UK, France, Spain, Sweden and Finland, two car manufacturers FIAT and Volvo, the machine tool manufacturer Goratu, the automation and maintenance services provider Zenon, and seven SME's representing related business areas.

The main challenge that DYNAMITE faces is related to the lack of flexible and cost-efficient maintenance systems also with current demands of flexible manufacturing systems in today's manufacturing industries. This challenge is related to many of the problems indicated above, but it is particularly linked to the low level of diffusion that advanced maintenance strategies, such as condition based maintenance (CBM) and predictive maintenance (PdM), have reached so far. According to Komonen (2005) about 30 % of all the maintenance activities in industrial and transportation systems in Europe are unplanned, whereas a 55% of the activities are related to planned and scheduled maintenance. That is, 85% of the maintenance strategies implies unnecessary action costs and machinery breakdowns or service actions like disassembly that have negative effects on the performance and lifetime of components. This leaves a maximum of 15% of the activities being focused on CBM strategies that presumably accounts for the newer and more critical machinery, where cost-benefit ratio clearly favours condition-based approaches.

Figure 2. The European DYNAMITE concept for future IT-based maintenance.



The DYNAMITE vision () aims at promoting a major change in the focus of condition based maintenance, essentially taking full advantage of recent advanced information technologies related to hardware, software and semantic information modelling. Special attention is also given to the identification of cost-effectiveness related to the upgraded CBM strategies, as well as to the inclusion of innovative technologies within CBM. It is expected that the combination of the use of new technologies with a clear indication of cost-benefit trade-off will facilitate the upgrade into CBM, in many cases where non-critical machinery exists, and especially for the vast majority of SME companies that feel the distance between planned maintenance and condition based is too wide.

The main technologies expected to facilitate this upgrade are wireless devices, such as smart tags and hand-held computing devices, micro-size MEMS sensors especially designed for maintenance purposes, and low-cost on-line lubrication analysis sensors. On the other hand, adequate information processing tools should take care of the continuous data flow and suggest appropriate actions to the operators. In order to provide the most convenient analysis flow, information processing is understood as a distributed and collaborative system, where three different levels of entities can undertake intelligence tasks (). At the lower end, sensors can provide certain degree of reasoning, taking into account the 'local' scope of this processing. At a medium level, smart PDAs (mobile agents) will provide higher communication interfaces with sensors, intermediate processing capabilities and a smart end for human interface to remote web services centres that will compose a distributed web platform system at the higher end of the processing hierarchy. Finally, wireless data transmission between sensor devices and information processing layers will be implemented.

As the complete DYNAMITE processing system is based on a distributed intelligence concept, is it clear that sensors and smart tags should perform only those data processing tasks that may handle more efficiently than upper intelligence layers. For instance, it is not in general easy to perform diagnosis at the sensor-level, as this diagnosis will be partially compared to what can be offered by PDAs or web services. On the other hand, it is expected to have signal processing capabilities at the sensing devices in many cases, as this will release communication throughput and computing resources for other tasks.

Also, given this global architecture, it is clear that the role of the mobile agent devices is very important within the e-maintenance concept linked to DYNAMITE project. On the other hand, the distributed DYNAMITE processing layers also pose some ‘system’ constraints on the use of such mobile agent devices. These should not act at the highest end of intelligence, but rather as a web-platform mobile interface with built-in local intelligence and inter-connected both with the central data-office, as well as with the monitored equipment, thus enabling engineering personnel to perform fast and efficient maintenance activities at the shop floor.

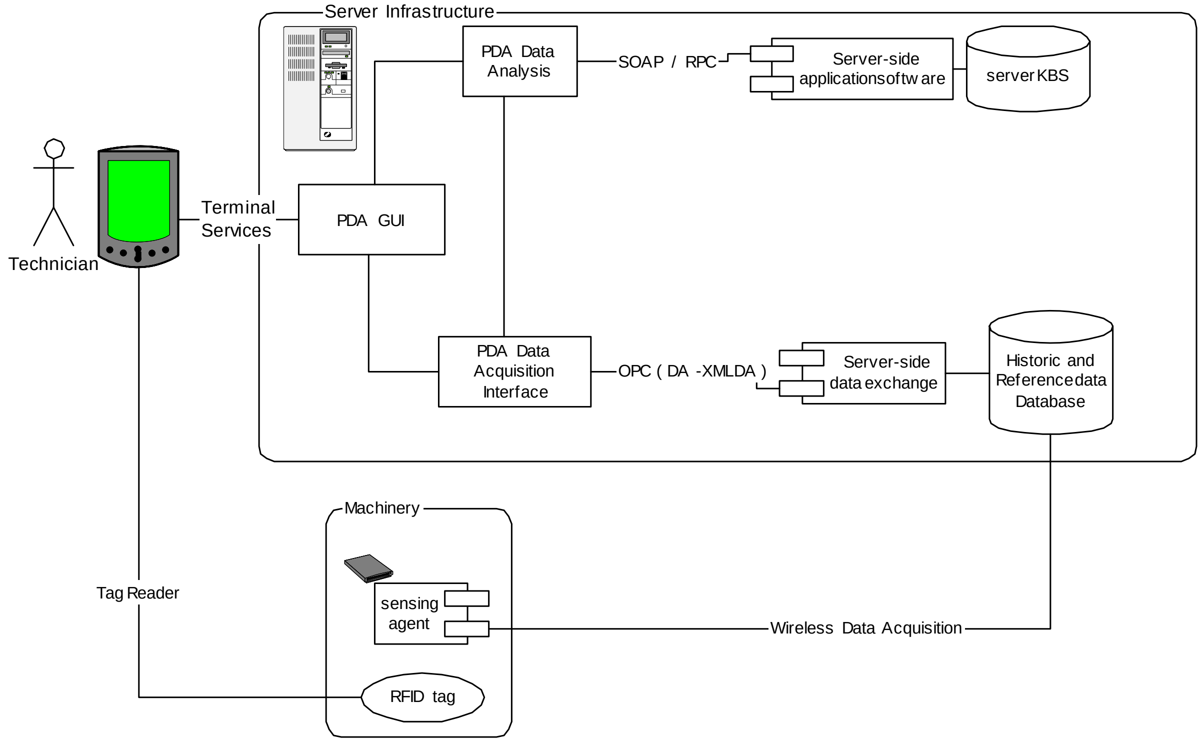
Mobile devices in maintenance management

Since their inception (Chess et al., 1995), mobile agents have been used in a wide variety of applications. There are several advantages in employing mobile computing compared to conventional wired computer applications. Among other, mobile computing offers the flexibility to initiate applications at flexible locations in unstructured networked environments, to quickly and efficiently search for and retrieve relevant information from heterogeneous data sources, to perform tasks while utilising limited or intermittent connectivity and to provide asynchronous services to client requests (Samaras, 2004). Adding the ease and flexibility of carrying a handheld wireless device, mobile computing has the potential to transform the way a range of industrial management, monitoring and control tasks are performed (Buse & Wu, 2004). This potential is still largely unexplored in maintenance management.

Although the usage of wireless devices within an e-maintenance framework has been suggested in the past (Lee, 2001), integrated maintenance management solutions based on combined usage of wireless sensing, RFID tags, hand-held devices and central or remote server-side computing and data-offices (Lampe et al. 2004, Legner & Thiesse, 2006, Wittenberg, 2003) are still in their infancy. Part of the difficulty is attributed to the challenge of integrating equipment, devices and computing resources and code from very heterogeneous sources (Bartelt et al., 2005, Trossen & Pavel, 2005) but also to the great complexity of optimising the management of maintenance in modern industry.

Within DYNAMITE, the usage of PDA devices plays a key role in bringing Mobile Maintenance Management closer to the daily practice at the shop floor. PDAs are used in synergy with intelligent sensing devices and smart tags on the lower-end of the data processing architecture, but also with central server's databases and data processing and remote access applications at the higher-end of the architecture. An example of the architecture functionality is provided in .

Figure 3. An example of the architecture functionality centred PDA.



Here the hand-held device is employed within a thin-client server architecture. The "mobile worker" (technician), equipped with the PDA, approaches the monitored machinery. The PDA is equipped with an RFID tag-reader enabling the automatic identification of the equipment/component and thus it becomes possible to automatically retrieve relevant data from the central system (Historic and Reference data Database) and quickly present it to the user. Furthermore, the PDA can access measurements logged to the intelligent sensing device (sensing agent) and combine/compare those with the automatically retrieved related historical and reference data from the central database, but also with domain knowledge from the central KBS (server KBS). Thus the PDA becomes a **ubiquitous expert advisor** and, at the same time, a flexible data collector. Within this architecture there can be several intelligent sensing devices, distributed across the plant, which can wirelessly transmit via short range RF either directly or indirectly via data logger gateways from the shop floor. In this manner, instead of an inflexible costly and rather inaccessible wired monitoring structure, we have a flexible, easy to deploy and operate wireless e-maintenance architecture, which can become a powerful, efficient and easy to use tool for the maintenance engineer, while at the same time can be integrated with the organisation ERP.

Functional range of available PDAs

Today there is a huge number of potential PDA hardware available. These can be divided into four principal subgroups:

1. Regular consumer PDAs
2. Retail / Logistics PDAs
3. Smart Phone PDAs
4. Custom Reference Platforms

Their features vary considerably, as it is summarised in .

Table 1. Comparison of the four main PDA subgroups.

Feature	Regular consumer PDAs	Retail / Logistics PDAs	Smart Phone PDAs	Custom Reference Platforms
1. Wireless 802.11	High-End	Yes (option)	Rare	Yes
2. SR Wireless	No (expansion)	No (expansion)	No (expansion)	No (expansion)
3. RFID reader	No (expansion)	Extra Option	No (expansion)	No (expansion)
4. Barcodes	No (expansion)	Yes	No	No
5. Display (VGA)	VGA	QVGA	QVGA	VGA (some)
6. Keypad/AlphNum	Some/Some	Yes/Some	Some/Some	Yes
7. Pen/OSK	Yes	Yes	Yes	Yes
8. Web Browsing	Yes	Yes	Yes	Yes
9. Powerful CPU	Yes(400+ MHz)	Yes	Some (~200MHz)	Yes (400+MHz)
10. Java/.Net	Some/Yes	Some/Yes	Yes / Yes	Option
11. Rugged Case	No	Yes	No	Option
12. Battery Life	No	Yes	Yes	Option
13. Common OS	Yes	Yes	Some	Option
14. Expansion Slots	Yes (one)	Yes (1+)	Some	Option

Notes

As can be observed by the table above the platforms coming from the logistics – retail sector tend to be richer in features, which are useful for industrial usage. Nonetheless, features which are still hard to find off the shelf are: short range wireless, RFID and barcode reader (except retail sector PDAs) and also PDA expansion slot availability. Such features are deemed important for mobile solutions tailored to serving industrial maintenance management needs and customised PDAs are necessary for the implementation of the mobile maintenance management concept.

CONCLUSION

In this paper the great changes of maintenance and its importance in supporting manufacturing industry have been discussed. First a short overview of the enabling tools and technology available to the maintenance engineer in manufacturing industry, in relation to the emergence of e-maintenance practices and the introduction of mobile computing was provided. Furthermore, the concepts of e-maintenance have been covered. The challenges of today's maintenance have been briefly described, highlighting a lack of industrial implementation of condition-based maintenance strategies. The potential of using ubiquitous computing in industrial maintenance practice has been discussed, followed by an outline of our vision for the adoption of mobile maintenance management solutions. This vision is supported today by the European Integrated Project DYNAMITE 017498 (Dynamic Decisions in Maintenance). One expected result is the development of prototype PDA-based mobile maintenance agent devices, which should operate within the e-maintenance architecture (with sensors, smart tags, CMMS, maintenance expert, ERP, MES) in order to bring mobile maintenance management closer to the daily practice at the shop floor. Experimentations will be carried out on Fiat and Volvo production sites in order to assess the impact of the e-maintenance architecture and mobile maintenance agent devices on maintenance management.

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