Maintenance Supported by Cyber-Physical Systems and Cloud Technology

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Abstract—**The paper discusses about the possibilities of Cyber-Physical Systems (CPS) and cloud technology in maintenance. Fairly new sensor solutions that could be used in maintenance and in interaction with CPS are also presented. Data models are important part of condition based maintenance (CBM) because the huge amount of data that is produced and thus also Machinery Information Management Open System Alliance (MIMOSA) Open System Architecture for Condition-Based Maintenance (OSA-CBM) standard architecture for transferring information is discussed.**

Keywords—Cyber-Physical Systems; CPS; Cloud; MEM; Piezofilm; MIMOSA; OSA-CBM

I. Introduction

The increase of complexity and cost of the current industrial equipment is becoming an important factor that is helping to change the maintenance from a corrective to a predictive maintenance strategy and more specifically to the CBM. This change is given more emphasis also by the increase in the requirements and the availability, performance and quality while trying to reduce the cost of the production equipment during its whole life cycle. A CBM system is based on monitoring the different parameters of an asset to compare to previously gathered data through various mathematical algorithms to do a diagnosis on the health level of the equipment and predict how it will behave in the future. This way, the downtimes of the machines can be programmed so that they affect in the least the production, decreasing the unpredicted production standstills and increasing the availability and consequently the Overall Equipment Effectiveness (OEE). The ultimate goal of a CBM system is to link it with the Computerized Maintenance Management System (CMMS) to take part in the maintenance by creating action reports for the technicians or shutting down a machine or reducing the speed if the system predicts it necessary.

The introduction of new technologies such as Micro Electro Mechanical Systems (MEMS) sensors and the constant price drops of these have enabled maintenance strategies such as CBM to become more and more popular and achievable during the last few years. Another aspect to take into account is the Internet of Things (IoT) that has allowed the communication between machines and the components that take part in an industrial plant. The IoT, while connected to the cloud technology, permits the users access the data from the CPS from anywhere and a wide range of devices. The focus of this paper is to reinforce the idea that a maintenance system supported by CPS and Cloud Technology can be beneficial in the increasing of the OEE and reducing the maintenance costs.

II. New Sensors

MEMS sensors are becoming more and more popular nowadays. With different MEMS sensors it is possible to measure a lot of different phenomena/things including temperature, acceleration, pressure, inertial forces, chemical species, magnetic fields, radiation, etc. [1]. MEMS sensors can be found from multiple different devices including handheld devices like mobile phones [2]. The name Micro Electro Mechanical System already reveals that MEMS are components that combine microelectronics and micromechanical parts together to a same packet. MEMS sensors are manufactured using the same methods as with Integrated Circuits (IC) and thus the price of individual sensor is relatively low [3].

According to big MEMS manufacturer the price difference for example in accelerometers can be really significant between MEMS accelerometers and piezoelectric accelerometers that are more commonly used in condition monitoring: the price of MEMS accelerometers is around tens of dollars and the price of piezoelectric accelerometers is measured in hundreds or even thousands of dollars [4]. MEMS sensors are light in weight, tiny, usually highly integrated devices, have low power consumption and works with low voltage [1]. The tininess of MEMS sensors is a huge advantage when sensors need to be integrated to small devices or measurements have to be made in tiny locations. In figure 1 can be seen MEMS accelerometer ADXL001 from Analog Devices attached to a printed circuit board, MEMS accelerometer KX122-1037 from Kionix and piezofilm accelerometer ACH01 from TE Connectivity.

However, it should be noted that when choosing a sensor great care must be taken that the sensor in question fulfils its tasks i.e. that is suitable for the monitoring purpose in question so that it is technically good enough to detect the early indications of faults, which quite often are hidden under other influencing factors.

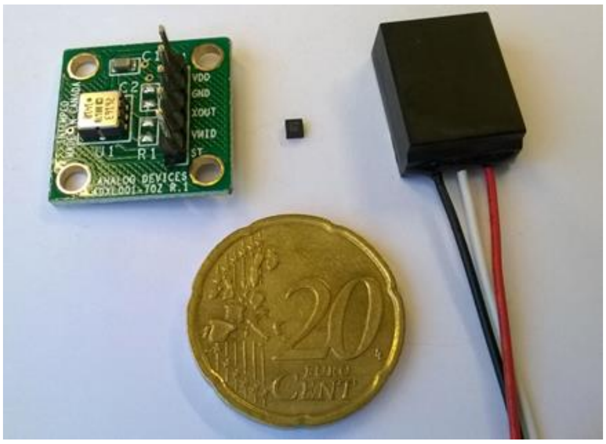

Fig. 1. Accelerometers from left: ADXL001, KX122-1037 and ACH01.

Vibration monitoring is very often used in CBM or predictive maintenance and it is especially suitable for monitoring the wear of the components of rotating machinery. This is due to the fact vibration measurements basically offer the opportunity to monitor both the amplitude and the frequency of the dynamic signal thus enabling the opportunity distinguish between various fault types especially by looking at the frequency they influencing. Examples of such fault types are unbalance (seen at rotational speed), misalignment (seen at the harmonics of the rotational speed), bearing faults (seen at the so-called bearing frequencies), and gear faults (seen the gear tooth frequencies) etc.

MEMS accelerometer seems to be an obvious choice instead of the more common piezoelectric accelerometer because of the price but MEMS accelerometer has it downsides also: usually MEMS accelerometer suffers from lower bandwidth, lower resonance frequency, poorer “off-the-shelf” protection against harsh and difficult measuring environment and higher noise compared to piezoelectric accelerometer. Depending on the demands of measurements, MEMS accelerometers might be more than good enough to replace piezoelectric accelerometers in some vibration measurement events. However, the opposite might also be true i.e. in case a very typical use the monitoring of bearing faults the demands for the sensor are very high because the impact a bearing fault causes in the beginning is very small and thus very difficult to detect [6]. At the same time the demand for early detection might be very demanding e.g. in case of offshore wind turbines the goal is to detect bearing fault a year ahead they would stop the turbine.

Another option for piezoelectric accelerometer in vibration monitoring is the piezofilm accelerometer. Piezofilm accelerometers are usually made of polyvinylidene fluoride (PVDF / PVF2) which is shaped in thin layers and those layers are coated with metal electrodes and plastic which protects the accelerometer [7]. Piezofilms are light, bendable, flexible, deformable, mechanically durable and easy to form for specific measuring location [8]. In figure 1 is shown ACH01 piezofilm accelerometer which is in a cover. Piezofilm accelerometers are valued in few dollars according to a big MEMS manufacturer Analog Devices and so they are even cheaper than MEMS accelerometers [4]. According to some piezofilm accelerometer data sheets it is possible to find quite promising accelerometer options for piezoelectric accelerometers which have high resonance frequencies (up to 35 kHz), wide bandwidth (for example 2 Hz - 20 kHz) and a low noise level that approaches the noise level of conventional piezoelectric accelerometer [9]. Even though these values look very promising the experience with piezofilm sensor is still limited when compared to the long history with piezoelectric sensors.

As indicated earlier in this paper care should be taken when choosing a sensor. This means that it is important to understand the function of the sensor and what kind of wear phenomena it is expected to pick up. When a clear understanding of the above exits theoretically and on paper the new sensor types will explode the use of sensors for condition monitoring purposes and this with the concept of CPS.

III. Cyber-Physical Systems

As it has been mentioned before, the main objective of a CBM system is to not just monitor the asset but to take direct action in the maintenance of the latter. If this requirement is fulfilled, the whole system is called a Cyber Physical System (CPS) because it integrates the monitoring of the equipment by computer-based algorithms with the internet and its users. It is hard to see the difference between CPS, machine to machine (M2M) and Wireless Sensors Networks (WSN) under the architecture of Internet of Things (IoT) but CPS is seen as an evolution of M2M systems [10]. Another term that can be associated to the ones mentioned above is s-maintenance (11). There exists a number of definition for this term see e.g. Karim’s doctoral thesis [12]. However, the simplest one is define e-maintenance as a technology through which maintenance is supported by IoT in order to get the information that is needed to the right place. Consequently, e-maintenance can be seen as a sub-category of IoT concentrated in to support maintenance activities. Following from the above, e-maintenance is the technology that in practise can enable the everyday use of CBM. Furthermore, CPS would into these definitions as the technology where the hardware and software form an intelligent solution that can perform task that are needed to carry out efficient CBM under the e-maintenance umbrella.

According to the U.S. National Science Foundation, “the term cyber-physical systems refers to the tight conjoining of and coordination between computational and physical resources”. The CPS in this case would consist of various components. A transducer or sensor that would measure a meaningful parameter of the asset to be monitored, linked to a data acquisition equipment, where, using mathematical algorithms the gathered signals are processed to obtain important data. Once the data are acquired, a diagnosis is made to evaluate the health level of the asset at that moment.

This diagnosis is based both on mathematical models of the real systems and also the previously gathered data that are stored in a database. The system should then be able to predict the future health states and the possible failure modes based on the current health level as well as historical data. It is worth mentioning that some companies are already offering solutions as a software platform that implement the data analysis and pattern recognition algorithms to help the integration of a CBM strategy with their system. Typically, these commercial solutions are able to carry out diagnosis of the condition of a certain set of components and fault types associated with them i.e. there is no prognosis element that would predict the future development of these faults.

With the diagnostics and prognostics information, the system could take pertinent actions to optimize the life of the asset. These actions could vary depending on the outcome of the system, from shutting down the engine to creating an action report with the instructions to change a component and send it to the maintenance technician that is available (closest) at that moment. The following will give an example of CPS:

"A filter was starting to get clogged causing an increase in the power consumption of the motor and an increase on the temperature. If the motor were to keep working at this level, soon the temperature would get to a point that was not permitted or could cause a breakdown or a risky situation. The system realized this and sent the maintenance technician a report with medium priority stating that the filter needed to be changed, gave definition of the location of the machine, reserved the tools needed for the repair and the spare parts that were going to be needed. It also scheduled maintenance for that equipment outside its working hours, so that the downtimes were reduced."

Today, it is possible to build a system that fully automatically caries out the above described tasks. In the Dynamic Decisions in Maintenance project which is document in the E-Maintenance book [11] all the necessary elements were covered. Naturally, since that project was completed the development of low cost sensors and low cost processors has been very rapid. Even though technically possible and today at a lower cost the above type of fully automatic solutions are not often used for other than very basic fault types for very cheap spare parts. In case of more sophisticated machines humans are always linked to the process so they can check that everything is going as it should. Also, the total number of solutions where the expected lifetime of components is predicted with reasonable accuracy is still rather limited.

IV. Cloud Technology

A. Cloud Service Providers

There are many different cloud service providers and among them are the big players Microsoft Azure, Google Cloud and Oracle. Cloud services are internet-based services that provide all the things that computer systems can offer. With cloud services, it is possible to get an access to big computing resources without the need of expertise of managing the computer system yourself. Cloud services can be accessed with any device that has an internet connection which is a big advantage. Cloud services typically offer protection against malicious programs which releases companies' resources to other duties.

B. Local Clouds

It is interesting that the concept of local clouds has not gained that much publicity. The fact is that an intranet solution i.e. the services that a company provides internally can be seen as a local cloud. In such a system, only the computers that are inside the local cloud have full access to the services which in principle are similar to the large commercial cloud systems mentioned earlier. It is typical that the local clouds can be accessed also by outsiders but when allowing this the IT departments of companies tend to have very strict rules and limitations.

From IoT, e-maintenance, and CBM point of this access to data within local clouds is an important question. For example, a machine tool manufacturer would like to provide maintenance services for the machine tools they have sold. In order to carry out maintenance in an efficient way they would like to use CBM strategy and thus follow the machine tools with CPS which in turn means that they need access to the data from the machine tools which as such can be considered as local clouds within the local clouds the end user has at their plant.

Recently quite a lot of discussion has taken lace related to these issues, the ownership of the data, security etc. A recent European project called Arrowhead has just ended and they have published a book [13] of their findings and developed solutions. The project was rather large with close to eighty partners and they have published their main results as open software in order to provide a solution to some of the above-named challenges.

C. Web Services

Normally cloud service providers also provide web-based services which strengthen the security between both the cloud and the web services. Web-based services make it possible to share the data from cloud servers to graphical user interfaces (GUI) for the end-user applications through the internet. Usually GUIs are used through web browsers. Web-based services integrate Web applications through the internet and they are created using server-side scripts (ASP, PHP, etc.) and client-side scripts (JavaScript, HTML, Flash, etc.). In figure 2 is a diagram of web-based service which shows the basic structure of web-based service.

There are Web services that are made more for industries like Open Platform Communications Unified Architecture (OPC UA). OPC UA is an industrial machine to machine (M2M) communication protocol developed by OPC foundation and as a web service it consists of an OPC client that interacts with an OPC server. OPC UA increases interoperability and is designed to be able to have real-time data access, historical data for analytics and reporting of data or events, and alarms, and conditions to notify when the alarm-trigger goes off.

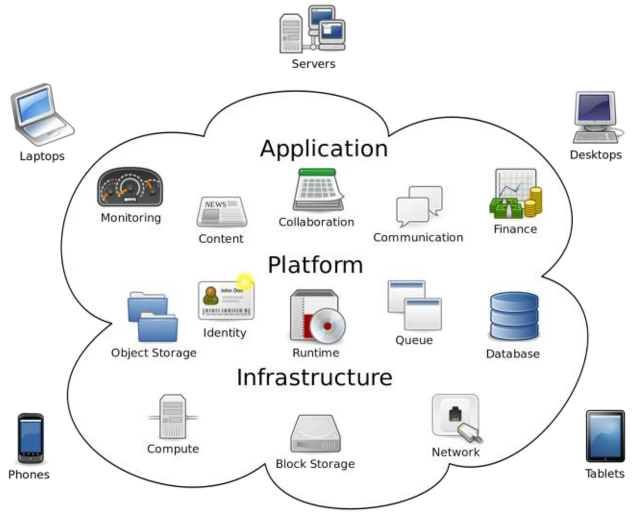

Fig. 2. Cloud computing [14]

OPC UA offers multi-threaded operations, a multi-platform implementation (ANSI C, Java, .NET) and new standard based security among others. High level of security of OPC UA includes, among others, sequencing, the use of end-to-end encryption, auditing and redundancy. The OPC foundation also provides members with Compliance Test Tools (CTTs) for test-case specifications, automated testing or interoperability workshops for tests with different vendors.

Another web service is representational state transfer (REST) which offers interoperability between computer systems on the internet. REST fully relies on the HTTP standard and thus it is usable by any device that support the HTTP standard and makes it easy to connect old and new devices as the protocol keeps the same. As REST fully relies on the HTTP it is compatible with intermediate components like firewalls, proxies and gateways.

D. Meta Data Model

A CBM system is composed of different elements, and each company might use a distinct way of connecting these elements and transmitting the information through them. This way to interconnect the different elements and pass the information has been called the "Meta Data Model". The solution to this problem is the standardization of the data models.

However, it can be claimed that standardization and meta-models are not the same way to ensure the interoperability in the exchanges of data during CBM processes. Indeed, three approaches can contribute to the improvement of inter-operability:

- the integrated approach based on the use of standard formats
- the unified approach which requires the definition of meta-models
- the federal approach which is based on the definition of ontologies whose implementations enable the dynamical adaptation of the systems

MIMOSA is one of the organizations that provides an open standard for information exchange between the plant and the machinery information systems. One of the advantage of using a standard is that components from different companies become interoperable and the compatibility issues disappear.

Even though MIMOSA is presented as defining standard format for the data exchange it also provides the Meta Data Model structure together with the definition of the ontologies of the data. In fact, one of the greatest benefits in using MIMOSA is this definition of semantics and ontologies so the party that is developing their CBM solution does not need to worry about how different type of information needs to linked together.

It can even be claimed that the whole foundations of a Computerized Maintenance Management System (CMMS) can be found defined in MIMOSA. Naturally, the one thing that is missing from MIMOSA so that it cannot be claimed to be a CMMS solution is the user interface which is the key factor in enabling the easy and efficient use of an CMMS solution in field i.e. the maintenance technicians cannot be expected to be using a database engine in their everyday work.

It should be noted that maintenance and especially condition monitoring data are very hierarchical i.e. when something is measured it needs to be linked to a component of a machine that is monitored. The component in turn needs to be linked into to the machine that is monitored. Also, the component needs to be linked to maintenance history data. Measured condition monitoring signal often needs to be linked with the measured process parameters so that the measuring condition can be defined. Then follow the signal analysis, diagnosis, and prognosis phases with the associated data. Further on the prognosis should lead to actions i.e. management of work orders and spare parts and so on. The UML descriptions that are available in www.mimosa.org give a nice inside view on this. It seems that quite often all of this is actually forgotten new condition monitoring solutions are developed together with new data structures.

OSA-CBM comes from the words Open System Architecture for Condition-Based Maintenance and it is a standard architecture for transferring information in CBM systems. OSA-CBM was developed in 2001 by an industry led team (participants from Boeing, Caterpillar, Rockwell Automation, different universities etc.) and it was partially funded by the Navy through a Dual Use Science and Technology (DUST) program. OSA-CBM was developed to standardize information exchange specifications within the community of CBM users and through that ideally drive the CBM supplier base to produce interchangeable hardware and software components and thus result to a free market for CBM components.

OSA-CBM has multiple benefits including cost reduction, increased specialization, increased competition and on the other hand it gives also a possibility to increase cooperation. Cost reduction comes through eliminating the need of system integrators and vendors to spend time creating new or proprietary architectures and through increased competition.

The OSA-CBM consists of multiple interoperable functional blocks as shown further and thus the whole CBM system doesn't have to be ordered from a single vendor but instead every block can be competed with different vendors. Also, smaller companies which are not capable to offer the whole CBM can take part of CBM system through providing functional blocks. On the other hand, interoperable functional blocks can increase cooperation. These multiple functional blocks give possibility to concentrate on smaller areas of CBM and so increase the quality of the whole CBM system.

OSA-CBM follows the ISO-13374 Condition monitoring and diagnostics of machines -- Data processing, communication and presentation -- -standard from the International Organization for Standardization. Table 1 shows the data-processing and information-flow blocks that are presented in ISO-13374 and that OSA-CBM also follows. The following paragraph will discuss about the individual blocks:

TABLE 1. OSA-CBM Functional blocks [15].

Data Acquisition (DA)
Data Manipulation (DM)
State Detection (SD)
Health Assessment (HA)
Prognostics Assessment (PA)
Advisory Generation (AG)

- **Data Acquisition**: The data acquisition is the first step in the different stages. It consists on getting the real world data into an electrical signal that can later be processed in a computer. This is done by transducers or sensors that can measure a wide range physical phenomena such as acceleration, position, temperature, pressure, etc. The signal that comes from the sensor needs to be suited and cleaned for an accurate representation of the physical phenomena, so it goes through different amplification or filtering stages as well as an analog to digital converter when necessary. Data is usually refined in a local server and then sent to the maintenance information center.

- **Data Manipulation**: Here the signal analysis is performed, where the meaningful descriptors from the gathered signals are computed and the virtual sensor readings are created from the raw signals from the Data Acquisition block.

- **State Detection**: It creates a "baseline" and compares the new data to the previously created profiles to detect if there are any abnormalities, and, if so, which profile the data belong to.

- **Health Assessment**: It diagnoses the faults and the current health level. It is usually done by analyzing the previously collected information such as health story trends, operational status or loading and maintenance history.

- **Prognostic Assessment**: This stage determines the future health state and the Remaining Useful Life (RUL) of the monitored asset. To be able to apply this stage, a wide range of initial data are needed on the possible failure types of the asset. The prognostic stage can be approached in two different ways: a model that describes the physical phenomena of degradation or a data-driven model where a pattern recognition system is implemented alongside machine learning techniques. Both approaches have their advantages and disadvantages, but often, both methods are combined to get the best result.

- **Advisory Generation**: It provides the information on what actions have to be carried out, or takes part in the actions required to optimize the life cycle of the asset or increase the Overall Equipment Effectiveness (OEE) of the plant by decreasing the downtimes of the equipment or the process.

V. Discussion

It is clear that the new technologies like new sensors, CPS and cloud technology will make an enormous change in how CBM can be taken in everyday use in the industry even in Small and Medium Size Enterprises (SMEs). Consequently, the economic potential is huge. In the forefront of this introduction of new technology is the manufacturing industry that produces intelligent production machinery.

The whole service business can in the future be based on these new technological solutions. Consequently, the OEE can be raised to a new level i.e. from 60 % to levels around 90 %. For the European industry, this is especially meaningful as there are numerous SME companies that rely on this type of production machinery.

By increasing the OEE to one and a half times what it has been is really a dramatic change which can be benefitted from in the global markets. As explained in the previous chapters the backbone of this change is the fact that with the new technologies all machines can be monitored and the maintenance can be based on the need and not on some statistics or guessing and at the same time sudden stoppages of production can be avoided.

The new technology can be used by personnel that are not experts of signal analysis or diagnosis and in cases where detailed and sophisticated knowledge is needed expert help can be called through the cloud and web services. It should be noted that the new technologies also remove the adverse influence of poorly done maintenance which today often is the cause failures.

First when following CBM strategy maintenance is not done in vain. With the new technology maintenance is always carried out to the right components using always the correct type of spare parts. The actual maintenance work can also be supported by new technological solutions like Virtual Reality (VR). Again, here it has been interesting to see how quickly the price of the needed hardware such as 3D glasses has dropped into a level where they can be used even at home for e.g. gaming purposes.

When considering what are the challenges in the introduction of the new technologies there are some:

- There will be high competition i.e. who will be the first to really introduce these new solutions in numbers.
- High competition might mean that not always the right technological solutions are made.
- Making the wrong solution might be expensive and a lot of time could be lost.
- When working in a hurry there is always the risk that short cuts are looked for and the results might then be very discouraging.
- If there will be numerous examples where the goals are not reached this will discourage the whole manufacturing industry.
- There are still technical challenges that have to be kept in mind e.g. even if all technology works the physics behind the need for maintenance have to be understood.
- When new technology is introduced companies are anxious to get financial benefit from it and it might be again discouraging if the time is longer than was originally expected.

VI. Conclusion

The paper describes the concept of CBM and CPS and how they are integrated together with the cloud computing in a maintenance system. Implementing a CPS will lead the industry to have more information on the monitored assets and, thus, more control over them. Not only this will help to reduce the downtime and increase the OEE, but it will also help the designers to create better equipment if the weak points are known.

As mentioned before, the new technologies such as MEMS sensors and the drop on the price of high processing power enable this type of maintenance strategy to be growing more popular. This, at the same time, allows the creation of new tools for said strategy, such as more powerful sensors or specific software.

Current trends suggest that the price of these devices is going to keep decreasing in the near future. Taking a look at the evolution of the industry, there is a high chance that the CPS are going to become a must in the sector.

In summary, the implementation of such a system will help increase the automation of the plant while carrying out the maintenance with as little disruption as possible and improve the design of the equipment.

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