Early-Warning System for Machine Failures: Self-Sufficient Radio Sensor Systems for Wireless Condition Monitoring

Michael Niedermayer, Eduard Armbruster
Fraunhofer Institute for Reliability and Microintegration, Berlin, Germany
niedermayer@izm.fraunhofer.de

Rainer Wirth, Axel Haubold
GfM Gesellschaft für Maschinendiagnose mbH
Berlin, Germany
wirth@maschinendiagnose.de

Stephan Benecke, Klaus Dieter Lang
BeCap
Technical University of Berlin
Berlin, Germany
tib421@tu-berlin.de

***Abstract* — European machinery products are in great demand due to their reliability. This competitive advantage can be further extended by using wireless sensor network for condition monitoring. Radio sensor nodes constantly monitor the aging of machines and detect faults before the machine fails. This means that time-consuming and expensive downtime can be avoided. A sensor network for the condition monitoring of industrial machines has been developed in the publicly funded project ECoMoS. The implemented sensor nodes are able to predict machine failures until 3 months in advance.**

Keywords-Energy Harvesting; Condition Monitoring; Machine Diagnosis; Wireless Sensor Networks

I. INTRODUCTION

Systems for condition monitoring should ideally identify malfunctions before the machine fails. Until now, this kind of sensor has only been used with high-end drives for cost reasons. The situation is changing with the availability of inexpensive, self-powered wireless solutions because the burden of such condition monitoring systems drops signify-cantly. This is especially true for upgrading existing production equipment whose unplanned downtime causes considerable costs. Furthermore, wireless sensor networks open up new opportunities by distributed data acquisition and communication. This offers the chance to revolutionize measurement technology in the coming years. In the joint project 'Energy-autarkic Condition Monitoring System' (ECoMoS), the application field of self-powered wireless sensor technology has been expanded to the wireless condition monitoring of industrial plants. A lot of research has been done to prepare this development. The preceding research activities focused on the implementation of sensor nodes with small size [1,2] at minimal costs [3,4] for industrial enviroments [5,6].

The rest of the paper is organized as follows: first, we discuss relevant aspects of vibration diagnosis in Section 2. Afterwards, prototypes for energy harvesting are presented in Section 3. Section 4 describes several implementation details of the wireless sensor network. Finally, Section 6 concludes our work and gives a perspective on our future work.

II. DETECTING MACHINE DAMAGES IN ADVANCE

Several measurement categories can be checked for the condition monitoring of machines. Temperature and vibration signals are most frequently analyzed to identify malfunctions of machines. Here, we focus on condition monitoring based on acceleration sensors which measure vibrations. The vibration diagnosis has been established for early prediction of machine breakdowns. The corresponding signal analysis methods are usually based on spectral analyses of the occurring mechanical vibrations. Two types of machine diagnosis can be distinguished regarding the accuracy. One variant, the basic diagnosis utilizes methods of simple characteristics. The second variant of condition monitoring applies an in-depth diagnosis to predict machine failures several weeks in advance. The higher accuracy can be achieved with the help of diagnostic algorithms, which use knowledge of kinematic drive models in addition to the analysis of vibration measurements. Condition monitoring systems for in-depth diagnosis are based on wired acceleration sensors, which are connected with diagnosis core units. There are only several wireless system solutions to run the less precise base diagnosis of machines.

The concept in the joint project ECoMoS (Fig. 1) is based on wireless condition monitoring using wireless sensor nodes [7]. The individual sensor nodes have the intelligence to carry out an in-depth diagnosis directly at the measuring position. This makes it possible to predict, for example, bearing damage by up to three months in advance. The sensor systems can be configured via radio transceiver and regularly send the machine state to a remote base station.

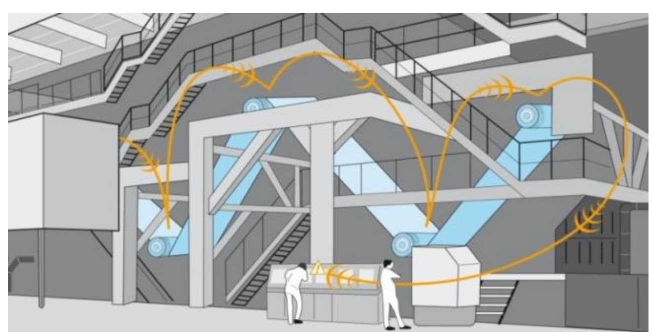

Figure 1. Condition monitoring of plants by wireless sensor networks

The complexity of the in-depth diagnosis drives the system requirements for the wireless sensor nodes to a large extent [8]. The vibration signal needs to be sampled at a frequency of 10 kilohertz and then digitized. At the same

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time, it is required to check whether the engine speed has remained within a tolerable range of about 0.5 percent during the measurement interval. If the change in rotational speed is greater, the measurement will be discarded. Since the measurement of the engine speed is performed by a different sensor, the speed values are transmitted before and after the vibration measurement of the wireless sensor node.

The spectrum of measured time signal has to be calculated by a fast Fourier transform (FFT, [9]) to later derive the envelope spectrum of the vibration signal. The abscissa of the spectrum can be replaced from sampling frequency to the fraction of the basic rotational speed to get the order spectrum. The critical multiples of the basic rotational speed are identified by a significance analysis. In a further step, it is checked whether these coincide with typical damage patterns. If errors are detected, e.g., irregularity on the inner ring of the roller bearing SKF 6309, the results of the diagnosis are transmitted in the form of feature vectors, comprising error code, kinematic frequency, significance level, and magnitude.

For the implementation of wireless sensor nodes that can perform this type of machine diagnostics directly at the measuring position, different circuit designs were evaluated regarding their energy efficiency. Some Digital Signal Processors (DSP) were capable of performing the algorithms for in-depth diagnosis more energy-efficiently than 16-bit microcontrollers, e.g., MSP430 from Texas Instruments, or 32-bit microcontrollers, e.g., AVR32 from Atmel. Hence the power consumption of the processor types could be compared for a number of FFT cycles with 1024 samples at a clock frequency of 1 MHz (Fig. 2). While the DSP based system architectures require significantly higher peak currents, the execution time is considerably shorter. This results from the special hardware support for filters and FFT calculations.

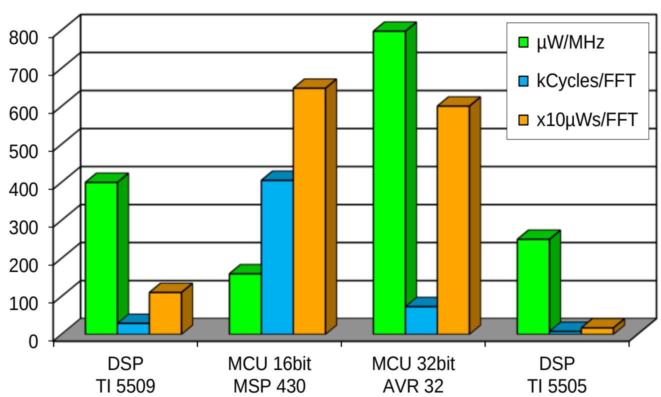

Figure 2. Comparison of different system architectures [10]

The analysis of analog circuit elements for data acquisition showed that the use of a DSP system architecture is the best solution to minimize the power consumption because the data from the acceleration sensor can be digitized immediately while the necessary filtering and scaling is left to the DSP. Another advantage of this approach is the increased flexibility in the evaluation of the measurement. It is thus possible to generate customized reports for specific measurement positions by parameterization with moderate effort. Fig. 3 summarizes the system architecture of the ECoMoS sensor nodes.

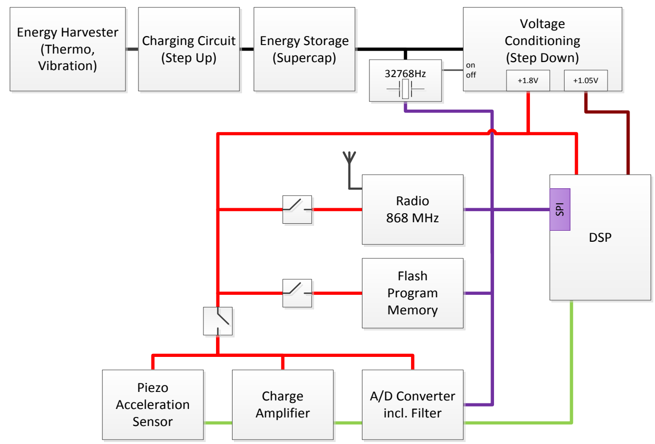

Figure 3. System architecture of the radio sensor nodes [10]

The selection of the appropriate sensor depended on accuracy of the measurement range, size, supply voltage, and power consumption. It was found that a piezoelectric acceleration sensor from IMI Sensors with charge output provides the preferred properties for the target application. Thus, a charge amplifier has been added to the input stage on the sensor node. This makes it possible to sample the machine vibrations with minimal energy consumption. Furthermore, the duration of the transient can be considerably shortened by a special discharge stage. This would not be possible for sensors with integrated amplifier.

III. Electric Energy from Vibrations and Temperature Differences

In addition to precise sensor, efficient data processing, and wireless connectivity, the power supply belongs to the key components for the development of maintenance-free wireless sensor nodes. The operating time of the wireless sensor nodes with batteries – depending on the duty cycle of the in-depth diagnoses – can reach several years by application of low-power components in combination with an optimized power management. However, there are several concerns regarding battery-powered wireless sensors especially in industrial environments. The users prefer solutions energy harvesting whenever possible. While solar cells can only be used in very clean industrial surroundings with little dust, thermal generators and vibration transducer provide a good way to convert the energy from the environment. This eliminates any effort for battery replacement and increases the operational reliability.

There are many different types of vibrations, which can be used for powering wireless sensor nodes in industrial environments. However, rigid structures should be chosen as measurement position for in-depth diagnosis of machines. This improves the precision of the diagnosis results but the magnitudes of vibrations on these locations are typically below 2m/s² (Fig. 4).

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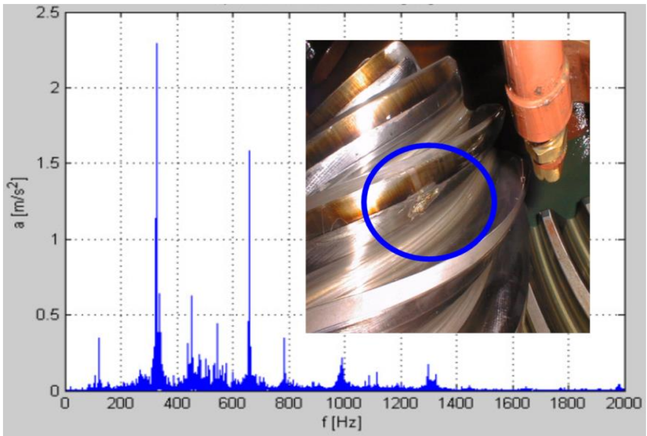

Figure 4. Exemplary acceleration spectrum of a typical drive

Most commercial vibration transducers are designed for a single resonance frequency between 50 and 120 Hertz. This means that such a narrowband converter cannot be used on each machine, since the efficiency massively decreases whenever the vibrations are not in the vicinity of the resonance frequency.

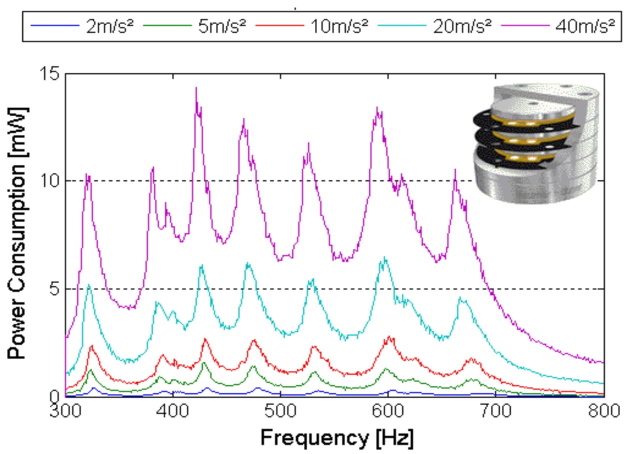

Figure 5. Design of a broadbane vibration transducer by stacking piezo elements [10]

A broadband vibration transducer (Fig. 5) has been developed in the ECoMoS project by skillful stacking piezoelements. The first prototypes of the vibration energy converter (Fig. 6) were tested with a tunable Shaker. It was found that the vibrations in the range of 300 to 800 Hertz provided enough energy to supply the radio sensor electronics. Such broadband transducers can be used more universally.

Significant temperature differences can often be found in industrial plants. Different drives have been examined under operational conditions regarding their temperature distribution (Fig. 7a) to develop very compact wireless sensor nodes with integrated thermal converter. It was considered what temperature differences occur directly on the thermocouple for typical measuring points by using a special test setup consisting of a reference heat sink and thermal converters with embedded temperature sensor. A temperature difference of only 3 ° C at the thermocouple was required to deliver enough energy for the power consumption of wireless sensor nodes for condition monitoring.

a) b)

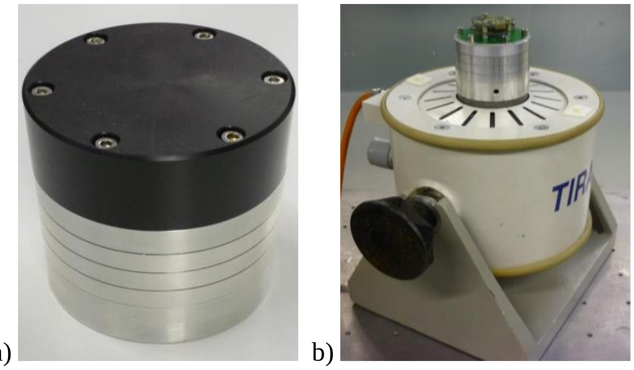

Figure 6. a) Implemented prototype of the vibration harvester, b) Vibration transducer characterisation, source: Baumer

a) b)

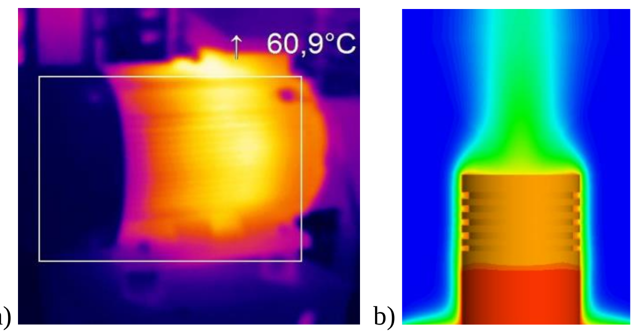

Figure 7. a) Temperature distribution during machine operations, b) Simulation of temperature distribution

The knowledge of the temperature distribution at the measuring points was applied in simulations to evaluate different assembly concepts (Fig. 7b). A robust housing with a diameter of only 4 centimeters was designed so that the hot and cold sides of the thermal converter are coupled particularly well with the industrial environment, without reducing the accuracy of the high-precision acceleration sensor (Fig. 8).

a) b)

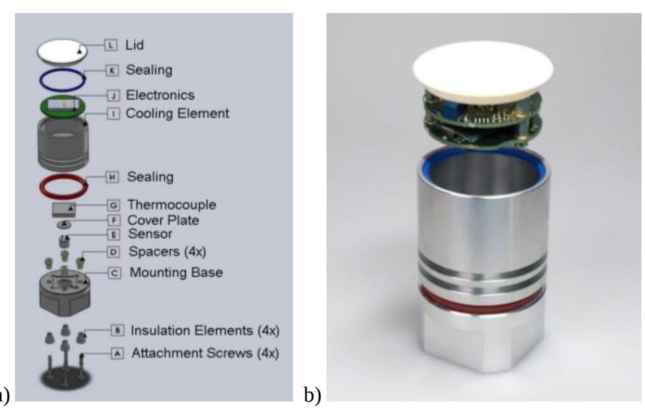

Figure 8. a) Assembly concept of the radio sensor system with integrated thermal energy havesting, b) Implemented prototype

A design tool has been implemented to facilitate the future development of wireless sensor systems with embedded energy harvesting. This software provides the system specific parameters from component library. The parameters can be adjusted by the hardware designer to layout the power supply of self-powered wireless sensor nodes. After selection of the conversion method, the type of physical size of the harvesting unit can be suitably configured. In addition, parasitic coupling effects are taken into account. In the example of the thermal converter, this applies to additional layers, (e.g., thermal paste and mounting adapter), which have to be taken into account for their impact on the energy efficiency (Fig. 9).

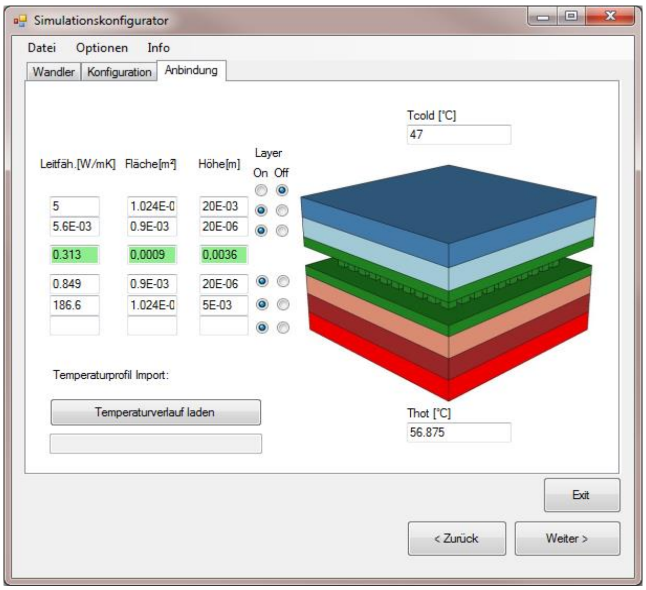

Figure 9. Selection of the energy converter and configuration

Following the energy conversion chain, the parameters for the voltage conditioning and energy storage can be queried. It is possible to select predefined voltage transformers. During simulation the input or output impedance at the operation point as well as the converted output voltage or current level are considered together with non-ideal effects of energy buffers such as leakage current and a parasitic internal resistance. In the input mask for configuration of the load, the clock frequency of the processor is to be set in order to determine the computation time for the individual algorithms. This approach allows for a first estimation of the energy performance of the wireless sensor node to determine the size of the power conversion stage and energy buffer so that particularly compact sizes can be realized inexpensively. The use of System-C for system modeling is also planned to investigate more complex algorithms in terms of energy requirements.

IV. INSTALLATION AND MAINTANENCE PER WIRELESS NETWORK

In production halls, there are many sources of interference that can affect radio transmission considerably. In the early days of radio communication, many problems regarding robustness of radio links occur in the industrial sector. This led initially to a high skepticism about wireless sensors, because the robustness of data transmission in industrial environments is particularly important. Meanwhile, there are various solutions to ensure robust radio communications. In particular, procedures at the protocol level of digital radio communication can reconstruct the correct data even when data erasure of multiple bits occurs. Therefore, the problem of robust data transmission is well under control in most cases, although the increase in energy efficiency of robust radio communication still remains an important research topic. An energy-efficient TDMA-based MAC protocol [11] has been applied. In this single-hop network, all sensor nodes receive a time schedule about the next communication interval from the base station.

The installation of wireless sensors can now be done quite comfortably. After attaching to a machine, sensor nodes identify existing wireless networks and log on. The operating parameters of the sensor systems, such as duty cycles, can be adjusted via the radio base station. A software update via radio link is also possible if new damage patterns or changes in communication protocols require reprograming the wireless sensor nodes. Thus, the user does not need to trigger a time-consuming firmware update for each individual sensor nodes via cable. Such a wired reprograming of sensor node can be very expensive especially for measurement positions, which are hard to reach.

For the preparation of the field tests, the prototypes were first tested in the laboratory by a tunable Shaker, which simulated the vibration profile of broken machines. The direct field trials were carried out in the harsh environment of a paper mill under realistic operating conditions in order to obtain more meaningful test results.

Figure 10. Paper plant in Spremberg [10]

On the site of the former gas conglomerate, Schwarze Pumpe, between Cottbus and Dresden, where earlier lignite was refined, paper production has been in full swing since April 2005. 170 million euros were invested to build the Spremberg mill. With a capacity of 330,000 tons of base paper per year, corrugated board is produced from 100 percent recycled paper. The preparation of a 1000 meter long and 5.4 meter wide paper web requires just a minute. Only one hour of downtime would cost 5,000 euros. Wireless technology significantly reduces material and installation costs for copper wire and cable channels about 100 meters total length of the paper machine (Fig. 10), that the initial investment for a wireless condition monitoring system offers a very short payback time.

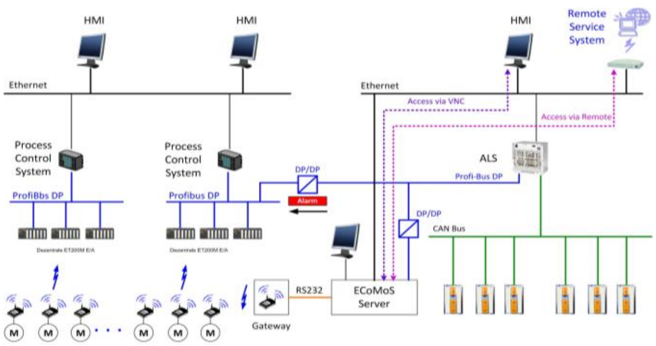

Figure 11. Integration of the ECoMoS sensor network into the process control system of the paper plant [10]

The fusion of data from the wireless sensor nodes is provided by the base station, the so-called ECoMoS server, which is connected by field bus with the control center of the paper machine (Fig. 11). During the installation of sensor node as well as the exchange of production components the kinematic parameters for the in-depth diagnosis has to be updated at the ECoMoS server. The ECoMoS server also receives the rotation speeds of the individual drives in the paper machine and transmits this data to the corresponding sensor nodes ted to the server ECoMoS. This procedure is done before and after each measuring interval.

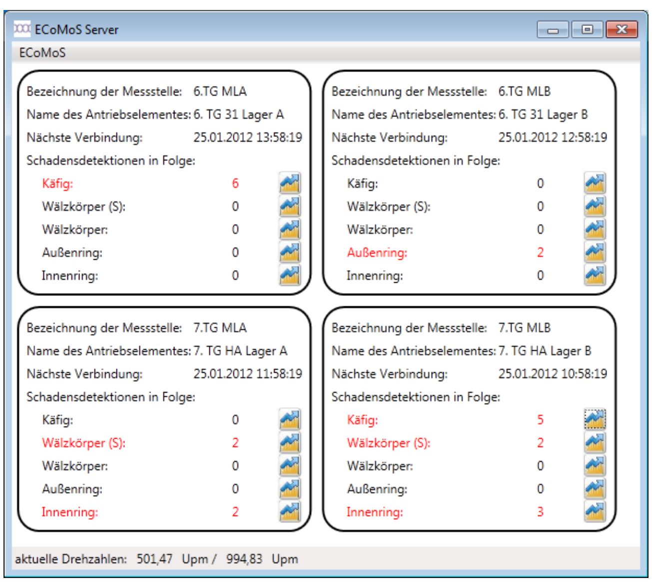

Figure 12. Result visualization of the in-depth diagnosis

If a damage pattern is detected, each sensor node can send the raw data via the base station and the ECoMoS server to the control center of the paper plant (Fig. 12). So, experts can examine the characteristics of serious errors in critical cases before costly actions for damage repair are initiated. Often, it is sufficient to replace a damaged bearing during the regular maintenance interval.

V. SUCCESSFUL PRACTICAL TEST IN THE PAPER FACTORY

In the first prototype generation, the system parts sensor, data processing, radio interface and power supply had been designed as modules to be tested in the paper mill separately. The second prototype generation as a compact complete system was implemented in 2012. Currently, the last work on the wireless protocol and the software for the ECoMoS server ECoMoS is nearly finished. Firstly, four measuring positions in the paper mills were equipped with the ECoMoS wireless sensor nodes to demonstrate a successful project completion (Fig. 13). Now, this sensor network will be progressively extended to the full configuration with 664 sensor nodes.

(a)

(b)

Figure 13. a) Field tests of the second prototype generation, b) ECoMoS-Server in operation

The wireless sensor network, developed ECoMoS project, can be used to detect wear of machines and plants that have drives, which are at least temporarily operated at a constant speed. There are many such manufacturing facilities. If later low-cost wireless sensor systems are available, condition monitoring will be used for additional rotating parts such as fans, which are not currently monitored due to cost reasons. The bill of material for such sensor node ranges from 10 to 300 euros depending on the requirements and environment. The cost of an entire sensor network, however, is mainly influenced by the production quantity. The development costs dominate the overall cost in niche applications. For a wide range of applications, however, such wireless sensor nodes will be produced in large quantities, so that the design and software costs only account for a small proportion of total costs.

VI. Conclusion

The aim of the joint project ECoMoS was to develop a wireless sensor network for the condition monitoring of industrial machines. The wide range of expertise in the fields of measurement technology, wireless communication, energy harvesting, module integration and machinery diagnosis were necessary to demonstrate the opportunities of modern wireless sensors for condition monitoring. The installation of sensor networks within plants provides the basis for advanced concepts in condition monitoring. Wireless solutions for machine diagnosis make it possible to reduce installation costs while collecting and evaluating more data on the individual sensors.

As such systems become available, the leverage effect for the construction of machines and plants becomes hard to predict. Such sensor networks will be connected with cloud services, so that the machine diagnosis can be supported by external service providers or the system manufacturer. The manufacturer would then be in a much better position to assess the reliability of their products. It can be observed, for instance, whether the construction of machine components needs to be improved, or whether it is possible to reduce costs, without impairing the reliability.

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