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Wireless Condition Monitoring for Industrial Applications based on Radio Sensor Nodes with Energy Harvesting

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***Abstract* — Wireless sensor nodes can detect component wear and tear just in time. Such sensor networks can allow for waiting to overhaul delay the overhauling of machines until it is really absolutely necessary. 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 three months in advance.**

Keywords* — *Energy Harvesting; Condition Monitoring; Machine Diagnosis; Wireless Sensor Networks

I. INTRODUCTION

With the availability of inexpensive, self-powered wireless sensor nodes the burden of condition monitoring systems drops significantly. The cost savings by introduction of wireless condition monitoring solutions can be considerable. Furthermore, new service concepts in conjunction with a maintenance cloud are enabled by a role-specific access to the sensor data and diagnostic results. Such cloud based sensor networks for condition monitoring will avoid time-consuming and expensive downtime of much industrial equipment in the near future. Sensor networks offer 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 [1]. A lot of research has been done to prepare this development. The preceeding research activities focused on the implementation of sensor nodes with small size [2][3] at minimal costs [4][5] for industrial enviroments [6][7].

The rest of the paper is organized as follows: first, we discuss relevant aspects of vibration diagnosis in Section II. Afterwards, prototypes for energy harvesting are presented in Section III. Section IV describes several implementation details of the wireless sensor network. The field test is introduced in Section V. Finally, Section VI 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. Vibration diagnosis was 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. In 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 few wireless system solutions to run the less precise base diagnosis of machines.

The concept in the joint project ECoMoS (see Fig. 1) is based on wireless condition monitoring using wireless sensor nodes [8]. 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.

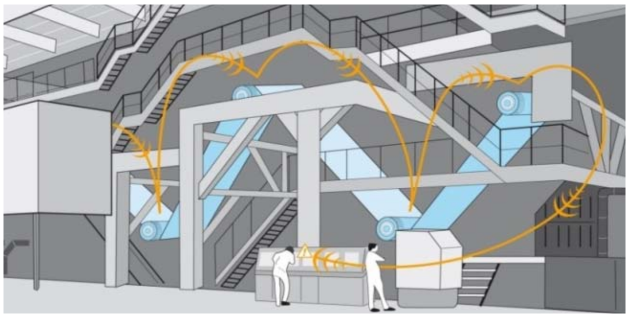


Figure 1. Condition monitoring of plants by wireless sensor networks

The complexity of the in-depth diagnosis drives the system requirements for the wireless sensor nodes to a large extent [9]. The vibration signal needs to be sampled at a frequency of 10 kHz and then digitized. At the same 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 the measured time signal has to be calculated by a Fast Fourier transform (FFT) [10] to later derive the envelope spectrum of the vibration signal. Whenever the engine speed remains in a tolerable range, the order spectrum can be determined by replacing the frequency in the spectrum abscissa with the basic rotational speed. The critical multiples of the basic rotational speed are identified by a significance analysis. In a subsequent 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 diagnostic directly at the measuring position, different circuit designs were evaluated regarding their energy ficiency. 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 (see 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.

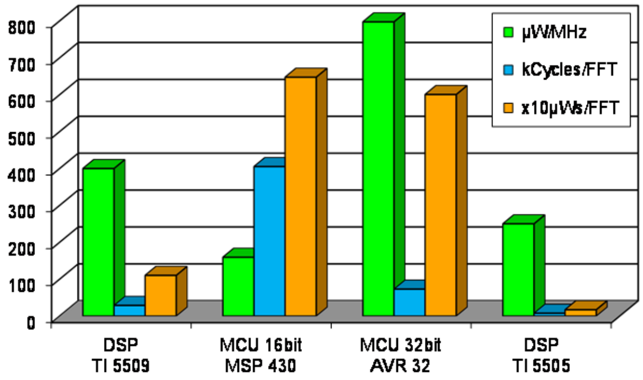


Figure 2. Comparison of different system architectures [11]

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.

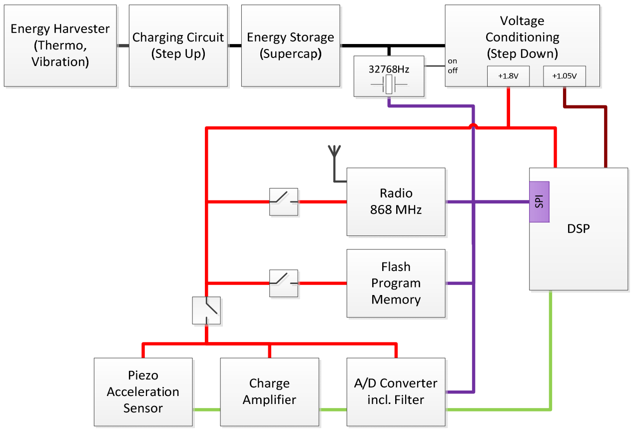


Figure 3. System architecture of the radio sensor nodes [11]

The selection of the appropriate sensor depends 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

Research and development in the area of micro-scale MEMS transducers is still ongoing with future potentials to satisfy steadily decreasing energy demands of microelectronic circuits [1]. However, depending on the ambient conditions available energy harvesting solutions with size constraints of a few centimeters already provide adequate voltage and current level. While solar cells achieve high power densities in direct sunlight, stability of solar irradiance is a challenging issue especially when designing technical solutions for a broader range of possible applications. Artificial lighting conditions, however, provide rather predictable illumination conditions, e.g., considering public buildings, workspaces, etc. Amorphous solar cells will deliver around 3µW/cm² at fluorescenting light with an illuminance of 200lux (machine hall) [12]. In case kinetic energy from vibrating objects such as engines, buildings or vehicles is available, resonant electromechanical transducers might be best suited. Piezoelectric transducers based on bimorph cantilever structures oscillating at resonant frequency of 120Hz and amplitude of vibration at 2.25m/s² deliver a power density of 375µW/cm³ on an ohmic load

[13]. Macro-scale assemblies of thermoelectric harvesters with total dimensions in the range of cubic centimeters consist of leg pairs of doped semiconductors that are mounted between two ceramic substrates and electrically connected in series. Subjected to a temperature gradient of 5K at 50°C a power density in the order of 590µW/cm² can be achieved [14].

As all harvesting technologies deliver an unstable output voltage depending on the available profile of energy inputs, a voltage converter is necessary in order to adapt to the requirements of the consuming electronics. In order to buffer energy, ultra-capacitors, accumulators or even a supporting primary battery might be an option, depending on the envisioned application. The storage unit should be designed to enable operation at times when ambient energy is not sufficiently available, but also to allow duty-cycle operation of the system. Another voltage converter at the output terminals of the energy buffer will regulate the output voltage provided to the energy consuming subsystems. A categorized schematic of the energy harvesting conversion chain is shown in Fig. 4.

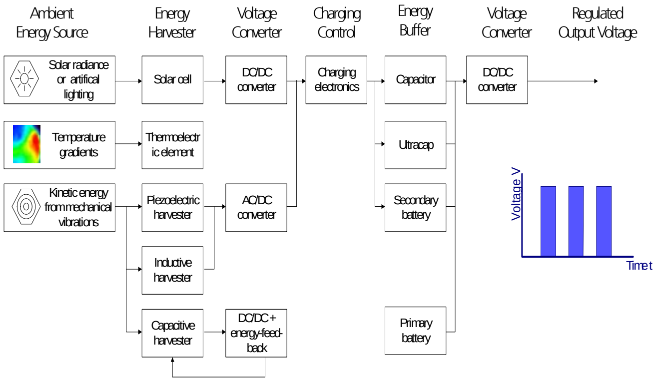


Figure 4. Schematic of the energy harvesting conversion chain

The introduction of energy harvesting technologies to wireless sensor nodes for condition monitoring purposes has the potential to overcome the current conflict between desired operating time and functionality [15]. To replace conventional battery-based solutions with energy harvestings systems on a broad basis, system behavior under realistic ambient conditions needs to be described by adequate models. Design approaches for self-sufficient sensor systems rely on the provision of sufficient power levels according to the specific boundary conditions determined by the application. In order to sufficiently describe the dynamic behavior of energy harvesting systems over its operating range, a modeling framework according to Fig. 5 was implemented as presented in [16]. Components of the conversion chain are modeled using parameter sets acquired from measurement to fully describe the devices over their operating range. The parameterized sub-models are then transformed into modeling platforms, e.g., Matlab/Simulink that provide capabilities for mutual modeling of different but connected physical domains. As a result, energy flows can be simulated based on the time history of the non-electric ambient energy source's intensity and the specific load profile of the power consuming electronics.

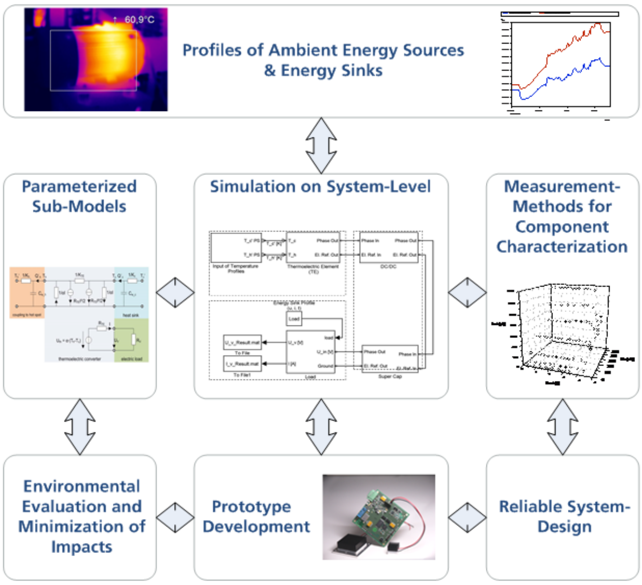


Figure 5. Concept of system-oriented modeling approach

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 [8]. Cycles of sleep-mode vs. active phase need to be adapted to the available power budgets. Fig. 6 exemplarily demonstrates the voltage level monitored at an ultra- capacitor used as an energy buffer in the application case described in this paper.

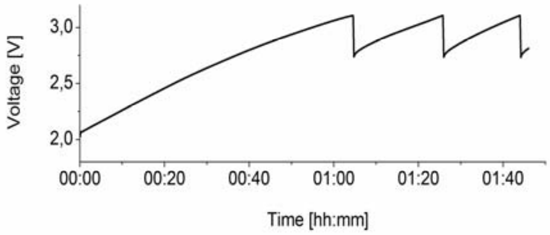


Figure 6. Voltage profile of ultra-capacitor during duty-cycle operation of the sensor node; field measurement

However, there are several concerns regarding battery-powered wireless sensors especially in industrial environments. The users prefer energy harvesting solutions whenever possible. While solar cells can only be used in very clean industrial surroundings with little dust, thermal generators and vibration transducers provide a good way to convert the energy from the environment. This eliminates any effort for battery replacement and increases the operational reliability. As thermal gradients and mechanical vibrations provide useful energy sources in industrial environments, concepts for a thermoelectric and piezoelectric energy harvesting device are described exemplarily in the following sections.

There are many different types of vibrations that 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 magnitude of vibrations on these locations is typically below $2m/s^2$ (see Fig. 7). Most commercial vibration transducers are designed for a single resonance frequency of between 50 and 120 Hz. 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.

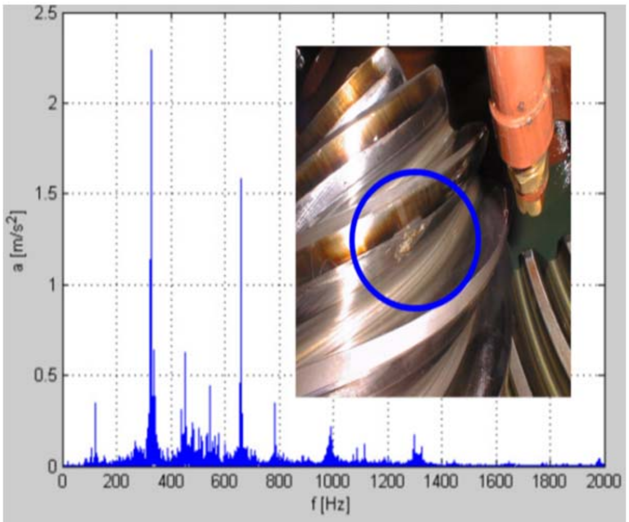


Figure 7. Exemplary acceleration spectrum of a typical drive

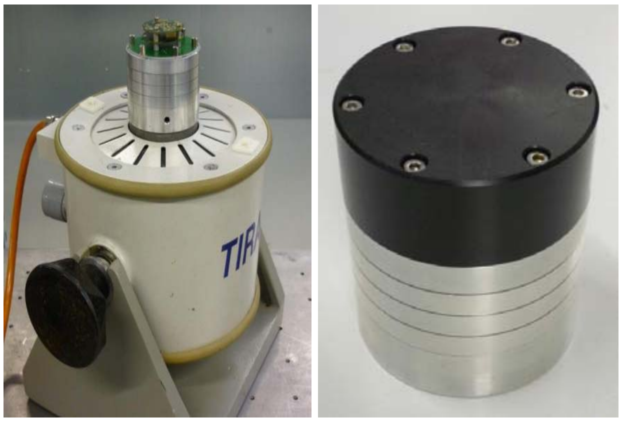


Figure 8. Prototype implementation of the vibration harvester, source: Baumer

A broadband vibration transducer (see Fig. 8) has been developed in the ECoMoS project by skillful stacking of piezo elements. The first prototypes of the vibration energy converter (see Fig. 9) were tested with a tunable Shaker. It was found that the vibrations in the range of 300 to 800 Hz provided enough energy to supply the radio sensor electronics. Such broadband transducers can be used more universally.

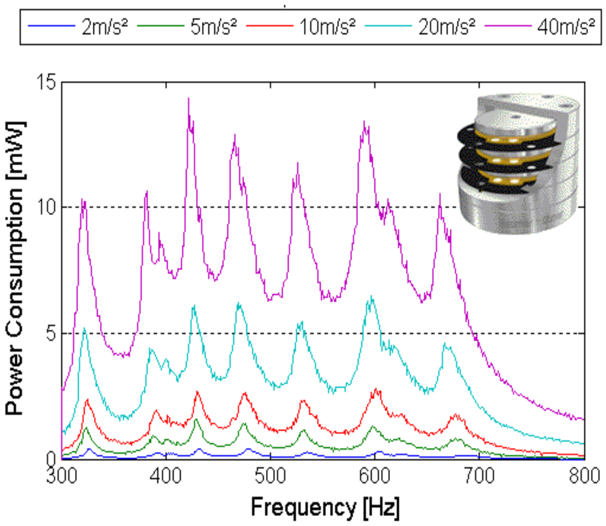


Figure 9. Design of a broadband vibration transducer by stacking piezo elements [10]

Significant temperature differences can often be found in industrial plants. Different drives were examined under operational conditions regarding their temperature distribution to develop very compact wireless sensor nodes with an integrated thermal converter. The temperature differences that occur directly on the thermocouple were observed for typical measuring points using a special test setup consisting of a reference heat sink and thermal converters with embedded temperature sensors. 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.

The developed concept for the sensor node shown in Fig. 10 provides integrated thermoelectric energy conversion capabilities allowing for fully autonomous operation. The concept is based on dual usage of the housing as both, protective holding of sensitive electronic components and the thermal path. In the center, a Bi_2Te_3-based thermoelectric device with edge-length of 20mm is mounted in between a bottom mounting base and a top cooler with integrated cavity for inclusion of the electronic system. The aluminum body with 58mm in diameter and a total height of 45mm is then mounted to a hot surface allowing for direction of heat flow orthogonal to the plane coupled to the hot spot. Screws for fixture of cooler and mounting base include thermally isolating sleeves and an isolating spacer defining a fixed height for thermoelectric module inclusion. Silicone-based heat-conductive pads are included on hot and cold sides of the thermoelectric modules to account for height tolerances by the manufacturer and provide damping when opposing the module to mechanical loads.

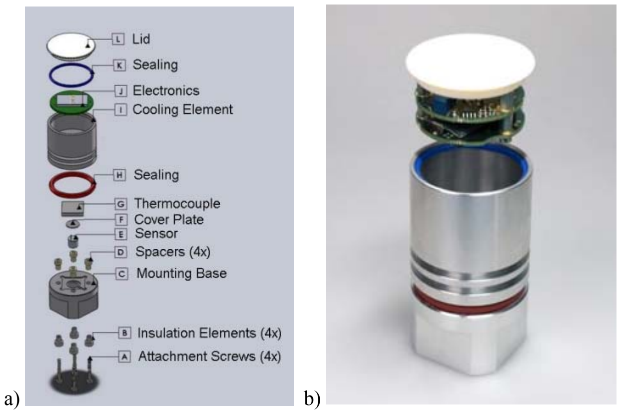


Figure 10. a) Assembly concept of the radio sensor system with integrated thermal energy havesting, b) Implemented prototype

Energy harvesting devices combine properties of different physical domains. The development of a multiphysics model suited to describe these domains simultaneously is therefore recommended. For the thermoelectric converter a suited model comprises the thermal path through couplings to heat source and –sink as well as the electrical side. Thermal voltage generated

$$U_{th} = \alpha_S \cdot (T_h - T_c) = \alpha_S \cdot dT \tag{1}$$

depends on the Seebeck coefficient α_S and the thermal difference between hot- and cold-side temperatures T_h and T_c respectively across the thermoelectric element. However, the thermoelectric figure of merit

$$ZT = \frac{\alpha_S^{\ 2}}{\lambda \cdot \rho} T \tag{2}$$

is a measure of a material's capability to efficiently generate electric power from temperature gradients. It depends on the thermal conductivity λ, and electrical conductivity ρ and absolute Temperature T.

By transformation using the analogy between thermal and electrical path a mutual modal can be derived that enables computation of electric voltage and current depending on the heat flow through the device as well as the peripheral electric circuitry. The setup of the electronic subsystem for voltage conversion and buffering was included in the analysis to simulate performance on system level.

Temperature distribution at the measuring points was applied in simulations to evaluate different assembly concepts (see Fig 11). In order to optimize the thermal properties of the housing computational fluid dynamics (CFD) software assuming varying ambient conditions was applied. The model was then used to calculate available temperature levels within the construction considering thermal interfaces and coupling to hot and cold sides. For this purpose a geometry model of the proposed solution was set up in ANSYS Icepak with the thermoelectric device being modeled with the elements shown in [10]. Material properties of metals and isolators were taken from Icepak library while specific heat conductivity of the thermoelectric element as well as the thermal interface material were determined from experiment. Boundary conditions resembling possible field conditions were set after applying a standard hexahedral mesh to the model.

All modules were aligned orthogonally to the z plane with the main direction of heat transfer in the z-direction. A constant temperature of T=61°C resembling available hot surfaces of industrial type engines was applied to the lower x-y-plane of the cabinet. The ambient temperature of surrounding medium at initial state was set to 35°C as measured in the machine hall. For simulation of natural convection effects, activation of gravity in the z-direction was considered. In the x-direction, the flow of fluid (air) particles was increased in four steps. In the worst case, the sensor node has to function at a solely natural convection. A typical velocity of v=0.2m/s was then increased in discrete steps to values of 0.5m/s and 1m/s resembling forced convection in the immediate environment of the devices, e.g., fans in the motor block available within immediate distance from the mounting base.

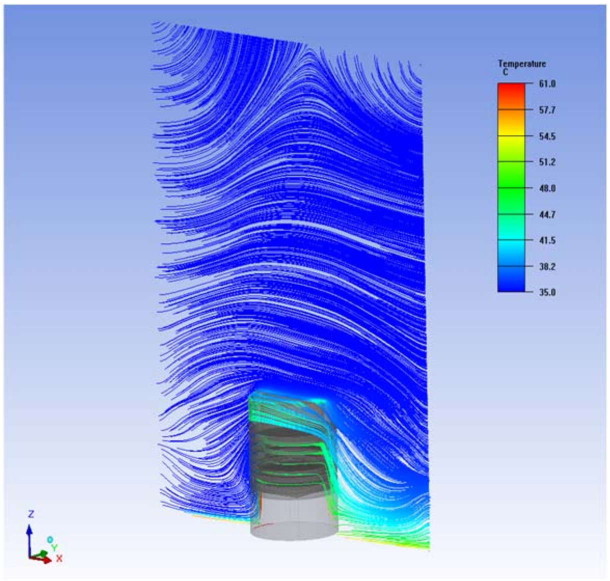


Figure 11. Simulation result of temperature distribution for a thermo-electric harvesting device at forced convection of v=1m/s

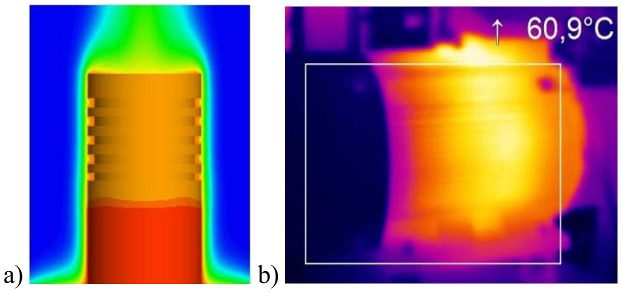


Figure 12. a) Simulation of temperature distribution, b) Temperature distribution during machine operations

Temperature distribution of running engines was determined by infrared-thermography (see Fig. 12). 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. 13 demonstrates the exemplary results of a simulation applied to the demonstrator. Average power provided to the consuming electronics at a constant voltage of 2.1V was calculated based on the simulation results of the system-oriented modeling concept using Matlab/Simulink (see Fig. 5).

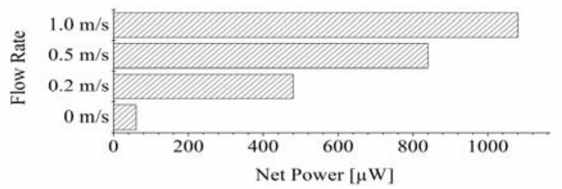
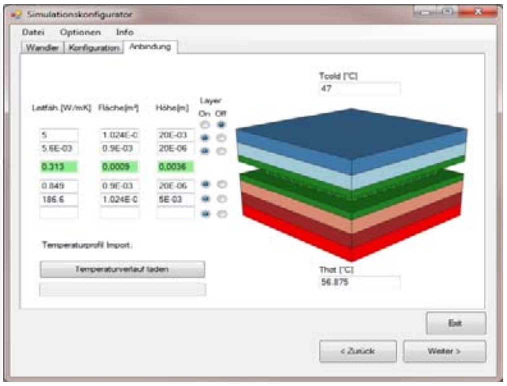


Figure 13. Continuous net power generated by the thermoelectric energy harvester

In the case of natural convection, only copper-based housing provided sufficient heat transfer within the thermal path. Choosing this option, voltage converted at the thermoelectric device was just above threshold value to start up the power management IC. Efficiency of the demonstrator was verified using a wind tunnel test setup with deviations below 10% from energy output simulation results.

A design tool for a first order approximation has been implemented to facilitate the future development of wireless sensor systems with embedded energy harvesting. This software provides the system specific parameters from the 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 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 (see Fig. 14).



Tcold [°C]: 47

Leitfäh [W/mK]	Fläche[m²]	Höhe[m]	Layer On	Layer Off
5	1.024E-0	20E-03	○	●
5.6E-03	0.9E-03	20E-06	●	○
0.313	0.0009	0.0036	●	○
0.849	0.9E-03	20E-06	●	○
186.6	1.024E-0	5E-03	●	○
			●	○

Thot [°C]: 56.875

Figure 14. 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 the 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 method can be seen as a supplementary tool to detailed system analysis as previously described. It is also planned to use System-C for system modeling to investigate more complex algorithms in terms of energy requirements.

IV. INSTALLATION AND MAINTENANCE 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 this manner, although the increase in energy efficiency of robust radio communication still remains an important research topic. An energy-efficient medium access control protocol based on Time Division Multiple Access [17] was applied here. In this single-hop network, all sensor nodes receive a time schedule about the next communication interval from the base station.

Security and trust are very important issues in industrial environments. The corresponding measures are currently under development. A secure wireless communication among the sensor nodes and the gateway will be ensured by AES encryption and unique identifiers for each device. The communication between the gateway and the private cloud server will be implemented using the OPC UA protocol stack. To assure a secure data access of the different users, a commercial solution such as CodeMeter® will be chosen for the license management in the cloud. This security approach guarantees diagnostic results based on trusted sensor data.

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.

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 for about 100 meters total length of the paper machine (see Fig. 15), that the initial investment for a wireless condition monitoring system offers a very short payback time.

Figure 15. Paper plant in Spremberg [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 (see Fig. 16). 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.

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. 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.

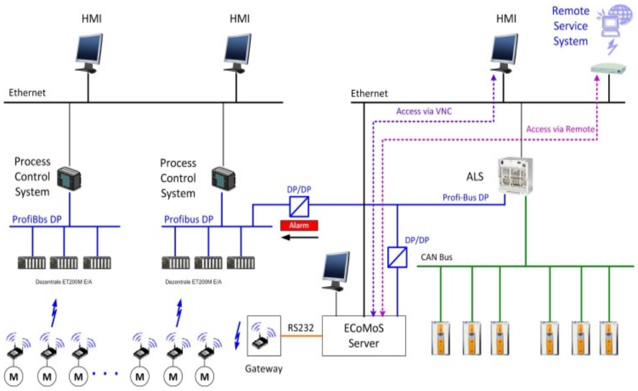


Figure 16. Integration of the ECoMoS sensor network into the process control system of the paper plant [10]

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 final prototype generation as a compact complete system was produced in February 2014. 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 (see Fig. 17). This sensor network can be extended to the full configuration with 664 sensor nodes.

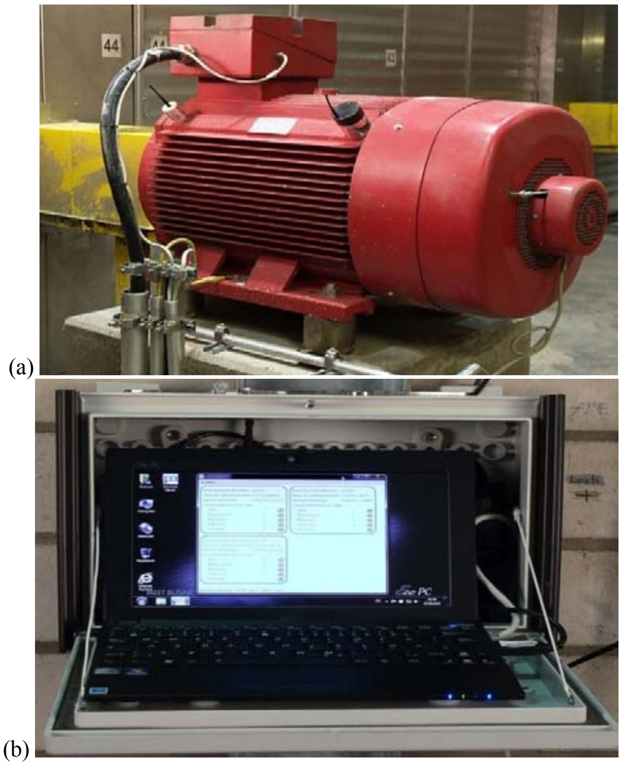


Figure 17. a) Field tests of the second prototype generation, b) ECoMoS-Server in operation

The wireless sensor network, developed by the 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. When in the future, low-cost wireless sensor systems will be 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 AND FUTURE WORK

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 by 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 or not the construction of machine components needs to be improved, or whether it is possible to reduce costs, without impairing the reliability.

Even if the use of radio sensor systems with artificial intelligence in production facilities is still to be regarded as visionary, highly miniaturized wireless sensor nodes for the future self-organization of production systems are under development.

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