NOVEL MICRO, WIRELESS, MEMS-BASED CONDITION MONITORING SYSTEM FOR MODERN MACHINE TOOLS WITH LIMITED ACCESS

Wojciech Staszewski, Adam Jablonski and Tomasz Barszcz
AGH University of Science and Technology
Department of Mechanical Engineering
Aleja Adama Mickiewicza 30
30-059 Kraków, Polska
Telephone: (48) 509-805-483
ajab@agh.edu.pl

Abstract: Currently available condition monitoring systems (CMS) offer many types of tools, including stationary systems, portable on-site instrumentation and finally wireless, autonomous systems. However, for a particular group of modern machine tools with limited access, like lathes, milling or grinding machines, none of this tools could be used due to limited access, space constraints and cabling restrictions. Firstly, stationary CMS use wires connecting vibration sensors with data acquisition unit (DAQ), which are prohibited by both, safety and topological reasons because of sealed door. Secondly, portable systems could not be used, because modern mining machinery is entirely closed, and a diagnostic engineer is not allowed to be present inside the machine housing while operating. Moreover, some of machines perform open lubrication, which makes supervised monitoring impossible due to constant lubricant splashes. Tertiary, currently available leading wireless sensors are characterized by relatively significant size, ca. 1.5 by 4 inch, and close to 10 oz. weight; therefore, introducing significant volume and mass to the machine spindle. Moreover, the rapid characteristics of the spindle movement would generate a significant inertia to the sensor causing extra vibrations and possible detriment to sensor mounting. For these reasons, modern machine tools are generally not equipped with external CMS systems.
Recently developed MEMS technology made it possible to design a novel, small-size unit, which is capable to work autonomously in environments with limited accessibility, where volume and weight matter. In contrast to commonly used piezoelectric accelerometers, MEMS vibration sensors need much less operational power, which is a major concern in wireless designs. Moreover, latest MEMS sensors are characterized by comparable frequency response to accelerometers. The short range wireless communication can be applied to avoid connecting cabling. The paper shows a prototype of a micro-size unit for data acquisition, data processing, data storage, and transfer. The prototype is evaluated on industrial lathe.

Key words: Condition monitoring system; diagnostics; microelectromechanical sensors; micro data acquisition system; portable machine health management tools; wireless vibration sensors

Introduction: Nowadays, in the highly industrialized age, the purpose of monitoring the conditions of an engineering systems, especially machinery has become a concern that requires great affection. A Condition Monitoring System (CMS) that bases on vibration monitoring may play a very important role in pushing out the maximum potential of all kinds of machinery by minimizing the downtime. As it has been widely shown in the literature, for instance in [1-3] the maintenance that bases on CMS in compare to traditional, scheduled or corrective maintenance, more accurately fits in many aspects only with few disadvantages. Unfortunately, the design and installation cost of condition monitoring system is substantial in comparison to other maintenance approaches; therefore, usually it is only used for a huge machinery, like turbo generators or wind turbines which downtime is extremely expensive The entire purpose is to show a potential for more affordable option for constructing a simple data logger, which might be eventually turned into a basic CMS, offering limited functionality that might lead into establishment of preventive maintenance approach, as well as provide a way to introduce such a system for machines for which it is currently impossible.

Condition Monitoring System: Condition monitoring (CM) can be shortly described as a process of monitoring a parameter of condition in machinery, like vibration, in order to identify a significant change in the range of this parameter which usually may indicate a progression of ongoing fault. As this process is a major component of well-known predictive maintenance, the use of CM allows to schedule a maintenance or undertake other actions to prevent further failure as well as avoid its consequences. Condition Monitoring has a benefit in compare to other techniques (breakdown and preventive (or scheduled) maintenance) – deterioration of the crucial parameters that would shorten a typical lifespan of a component can be addressed before they could develop into a major failure [4], causing an unplanned downtime. Condition monitoring techniques are usually used on rotating machinery and other equipment like pumps, electric motors, internal combustion engines, presses, while periodic inspection using non-destructive testing techniques are used for stationary plant equipment such as steam boilers, piping and heat exchangers. The advantages that have been offered by the application of predictive maintenance techniques have in a past few years led to the increase in the development of a number of methods for condition monitoring/fault-diagnostic systems [5]. After detection of possible failure (significant change of monitored parameter), mostly the diagnostic staff is responsible for taking the necessary actions in order to verify the condition of the machinery and later on act accordingly to prevent from machine failure. Those activities may require further data measurement in order to gather more data that might be necessary in order to make appropriate decision regarding machines condition, but at the point where the failure starts to develop it is necessary to notify the engineers that the condition of machinery is changing. The schematic of a modern condition monitoring system is presented in the Figure 1. Nowadays, the new methods of modern systems theory show that use of the mathematical process and signal models, identification and estimation methods can provide better, more accurate and faster available information regarding machine condition. With use of theme it is possible to establish new, advanced methods of fault detection and diagnosis in order to detect even small faults that occur quite early and to diagnose their origins in order to settle the primary cause [1].

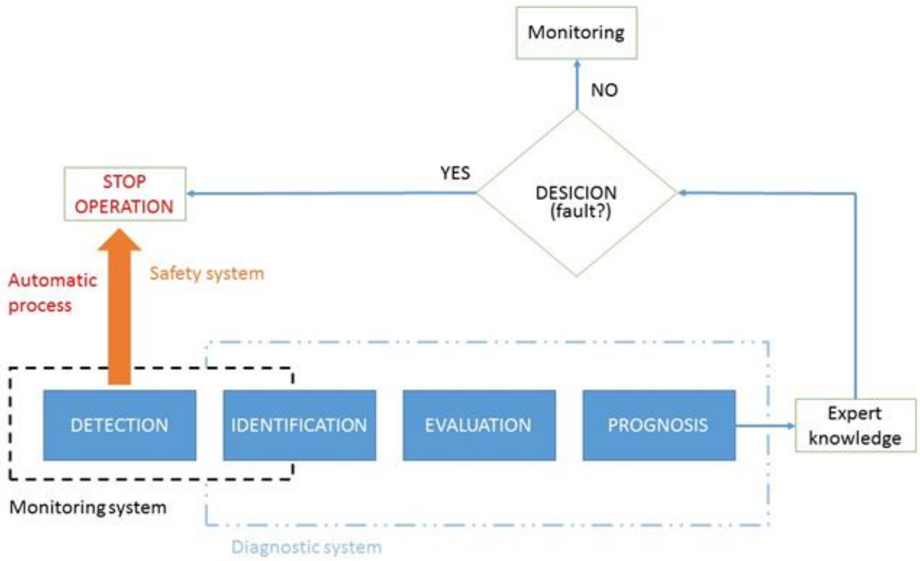

Figure 1: Scheme of modern condition monitoring system.

The process of automatic supervision of machines state is mostly realized by the limit checking (or threshold checking) of some variables that have been established as crucial for failure identification, e.g. force, speed, pressure, liquid level, temperature. Usually the alarms are raised when the limit value for a specific parameter is exceeded – before that a warning indicator may indicate, that condition is changing [3]. This process enables the introduction of automatic protection system, which in the moment of failure detection (exceeding the threshold value) will power down the machine in order to prevent from further damage, if it would harm workers or could cause permanent damage to the machinery.

Microelectomechanical Systems (MEMS) – it is compelling: As it was mentioned before, the condition monitoring systems are usually introduced for the machines that are huge in size and usually cost much, where the implementation and deployment of continuous monitoring may provide significantly lower service cost and drastically decrease maintenance time. The low cost system based on MEMS accelerometers such as the one considered in this paper could be the solution for smaller machines. The Micro Electro-Mechanical System (MEMS) based condition monitoring systems could easily reduce the installation cost per each node from $1000's to $100's [6]. The MEMS based sensors offer the capability to interconnect various interfaces used nowadays in the industrial applications and simplify implementation for considered systems. The MEMS technology is compelling, because of its attributes, such as size, weight, power, cost and high levels of functionality [7], but unfortunately their presence on the market has been limited because of relatively low level of performance in terms of noise density and resonant frequencies – in compare to other solutions, like piezoelectric accelerometers. High frequency MEMS accelerometers have been available on the market since few years, offering resonant frequencies as high as 22 kHz and Full Scale Ranges up to ±500g – unfortunately with the presence of high noise levels. Contrarily, available low noise

MEMS sensors have low resonant frequency operation, used for some condition monitoring systems, where its application requires very low frequency operation, which of course limits the possibilities of diagnostic evaluation [8].
The investment and further development in MEMS process technology has advanced to the point where the improvements in performance obtained via technology development are enough to make MEMS a new available option for a wider range of CMS applications. MEMS sensors are nowadays also tolerant to the shock conditions, with stable sensitivity after subjecting to 1000's g's of shock, or vibration to 10's of kHz. The accelerometers with embedded signal conditioning generally offer a full electrostatic self-test of the moving element and signal conditioning circuits.
In order to affirm the thesis, that MEMS accelerometers could be easily used for own-made condition monitoring system the test case has been established based on a measurement of a simple domestic fan with an office clip attached to one of its blades serving as an imbalance. Two configurations have been used in order to gather measurement data: (i) the professional ACQ unit "Vibmonitor" equipped with 24bit ADC and industrial piezoelectric accelerometer IMI 61A02, (ii) proposed system with 12bit ADC and ADXL001-70 MEMS accelerometer. To point out, the main imbalance component is well preserved in MEMS measurement. However, the representation of higher components is worse than in case of piezoelectric accelerometer (used in a professional system), because of additional damping since the latest development of MEMS sensors is available only as a raw electronic board; therefore, in order to preserve high spectral bandwidth, it is necessary to develop a housing with relatively slow damping.

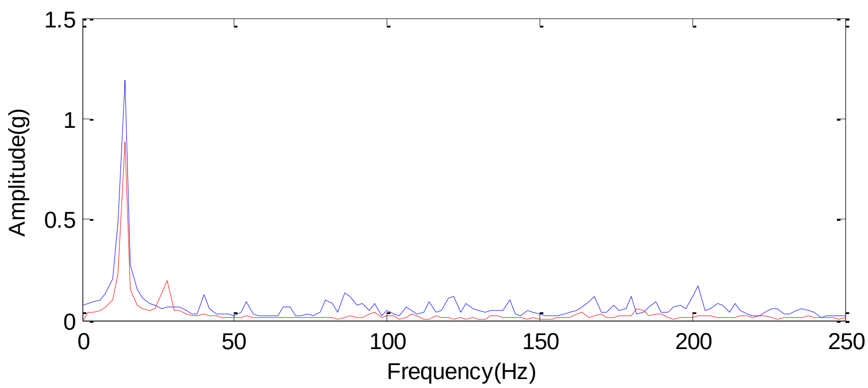

Figure 2: Comparison of results obtained in a lab with use of professional measurement system and own-made single-point sensor and daq.

Single-point sensor and data acquisition unit: For many years, in order to achieve very accurate measurement of vibration signals of individual components of the machine in the industrial conditions, the maintenance engineers were obligated to use very expensive equipment. Those appliances very often exceed the budget for the maintenance process and there-fore only for a few cases those solutions have been used. That is why the authors came to a conclusion that there is an enormous market to create low-cost architecture of data-acquisition device that could work in the industrial environment. The authors have been listening requirements and requests from companies and truly understood the need for this kind of cheap and accurate device. At the beginning it was necessary to focus primarily on the selection of appropriate architecture of data-acquisition device. Microprocessor STM32 caught authors' attention during the long process of selection the main heart and brain of whole system. STM32 exceeds many different solutions and microcontrollers due to its powerful tools, embedded possibilities and obviously very low price. The research was based on STM32 version F401re which is working on ARM M4 Cortex and the maximum system core clock is 84Mhz which seems to be fine for own-made systems. The key features of ARM Cortex M4 are presented in Table 1.

Table 1: ARM Cortex M4 features.

Parameters
up to 96 Kbyte of SRAM,
1.7 to 3.6V application supply and I/Os,
Power consumption of run mode: 146microA/MHz,
1 x 12 bit, 2.4 MSPS A/D Converter,
General-purpose DMA,
Up to 10 timers,
RTC

For the sake of the measurements, the STM32f401re NUCLEO board was used that bases on ARM Cortex M4 considering the following criteria (comparing to ARM Cortex M7):

- At the moment when the development was started the price of chosen M4 based solution was around half the price of M7 one and the idea behind the single-point sensor and daq is to cut costs as much as possible, while preserving functionality and decent accuracy,
- The main considered parameter (speed) of the ADCs present on both M4 and M7 is comparable (~2.4MSPS),
- The other parameters of ADCs have not been considered as it was out of the scope of this paper,
- Despite the fact that M7 has bigger flash, the idea is to either store the measurement data on SD card or (after further development) send the data on-line, using wireless protocols and therefore it was not crucial for this project.

In the Figure 3 the conceptual design of a single-point measurement and data acquisition unit is presented.

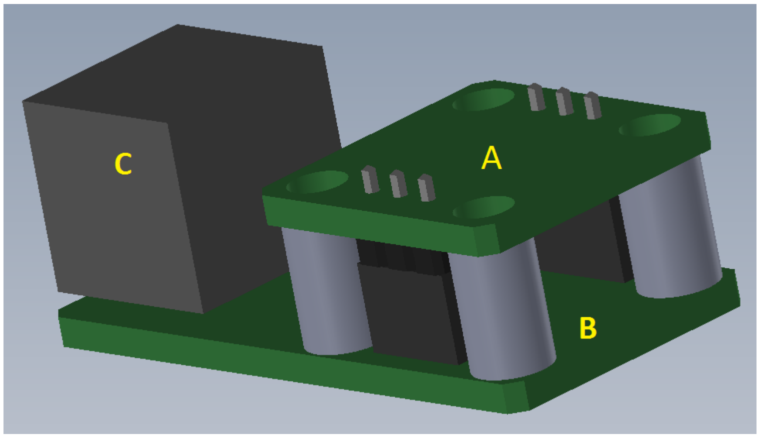

Figure 3: Scheme of single-point sensor and daq device: A – accelerometer, B – processing unit, C – connectivity.

Development of portable, wireless MEMS-based sensor: A typical low energy (LE) application involves sending the sensor data from a LE peripheral device (such as a smart monitor) to a LE Central device (such as a smartphone, or central DAQ). The architecture on the system level of such a device for needed applications has three major functional blocks, as shown in the Figure 4: measurement, data and event processing, and connectivity. Each considered block supplements to the average current of the overall system.

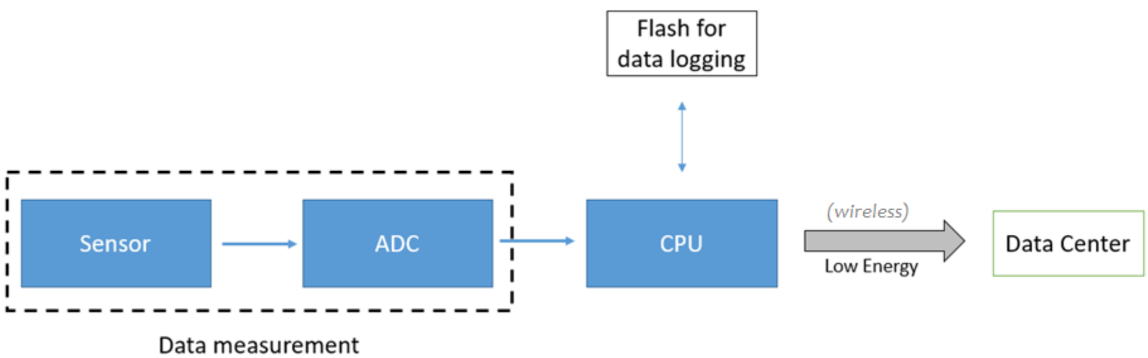

Figure 4: System Block Diagram for wireless sensor.

The measurement (sensing) block is composed of a sensor (MEMS accelerometer) and transducer hardware that converts the sensor information (digital signal) into an analog, electrical signal. A transducer is followed by a circuit that is used for data filtration and amplification (signal-conditioning circuit). The conditioned analog signal is converted into digital data for processing by an analog-to-digital converter (ADC). The main, key factors that regulate the overall current consumption in the sensing operation are: (a) signal conditioning and analog-to-digital conversion - the ADC consume significant current, (b) sampling rate - necessary to have enough samples for accurate processing of the data, (c) scan rate - the rate to detect an activity, which allows to save power when

there is no sensing activity in the system. The data acquired from the sensor requires processing in order to get a meaningful information. It may also be necessary to compress the data to reduce the bandwidth required to transfer the data to the central device (over-the-air data transfer). Furthermore, a LE device might use more than one sensing unit. In such a case it is necessary to detect pending activity in multiple sensors, process the data from multiple sensing points, and send the measurement data over the LE link. Each sensor's scan rate can be synchronous (with some limitations) and asynchronous to the others and the LE link. The knowledge how to efficiently manage those activities might be a crucial factor that contributes to the overall current consumption and leading into increase in the possible lifetime of the device on single battery.
The LE communication enables to send the measurement data from a sensor to a central device through the notifications or send read requests from the central device to the sensing device. The time taken to process the notifications and send the measurement data to the central device efficiently will at the end determine the overall current consumption.

Wireless Low Energy – increasing battery life resulting in extending operational time for each device: It is apparent that battery life can be increased by using mainly the following two approaches that lead to reduction the average current consumption: (a) reduce the active mode current: The data measurement and data processing functions contribute almost equally to the overall system current consumption and therefore, it should be a priority to reduce the current consumption in active operations - sensing, processing, and transmission, (b) reduce the active time: Reduce the time spent for active operations in CPU or RF resulting in longer idle state of the system. The actual current consumption in these idle (or sleep) states is as important as the current consumed during active operations. The overall current consumption could be limited by using the low-power modes as often and for as long as possible. The device can the following states, distinguished by the current usage:

- (i) The Active state stand for that all the scanning and processing activities are carried out at the highest required rate.
- (ii) The Idle state saves power when the device in not being used for an idle period (an interval, after which the device goes into idle mode).
- (iii) The system and LE connection are in the Deep-Sleep mode for most of the time.
- (iv) When the battery voltage drops below the operable voltage, the system stops all the activities and shuts down.

The final application should be designed in a manner to allow the CPU to operate at lower clock frequencies in order to reduce the current usage. The power-optimal algorithms and implementations should be implemented and tuned for the CPU architecture to reduce the actual processing power required for sensor data processing and not to exceed the needs. The algorithm can put the unused peripherals and clocks into the available low-power modes permanently. In addition, peripherals and clocks that are not required often or that are required only in specific usage modes should be put into their lowest power modes, wherever possible. Therefore, the application should have an algorithm that will allow to change the current operation mode as often as possible in order to reduce the overall current usage and to extend the battery lifetime.

The application should align the sensing and data processing operations to the beginning or end of LE connection events. The application can then complete all the processing and put the system into the Deep-Sleep mode along with the BLESS until the next LE connection event. This is more power efficient than processing asynchronous to the LE events, because it allows the system to be in the Deep-Sleep mode for longer times.
If no sensor use or activity is detected for some time, the device can reduce the rate at which it scans for the activity. In addition, it can increase the connection interval of the LE link and enter low-power modes to reduce the system current. While this may introduce latency in reacting when an activity occurs, the overall system power can be significantly reduced.

The sampling rate of the ADC in the device should be reduced to the minimum frequency required to effectively reproduce the analog signal being sampled. Based on the sampling frequency, the ADC configurations that allow low-power operation should be used. In addition, the channel resolution can also be reduced to decrease the conversion time and thus save power.

Conclusion: The conducted study on the use of low cost MEMS-based accelerometer solutions for the purpose of building cheap, portable and power-efficient condition monitoring system that could be applied in the conditions where typical systems cannot be introduced shows an approach of own-made system, suitable for different scenarios. The presented concept of a device that can support multiple systems and LE low-power modes that enable to design a highly power-efficient solution. Wireless low energy brings the wireless connectivity to low cost, small battery operated devices that require months or even years of battery lifetime. It has been designed to address the needs of energy efficiency and simplicity of design when employing it to develop connected products. The battery life of a LE application depends on the system-level current consumption. In most applications, sensing and processing can consume more power than the LE operations, so attention must be paid to reduce the overall system current.

The concept of creating own-made condition monitoring system that bases on portable, wireless sensors embedded with wireless low energy shows the potential of this technology. Not only could the presented realization be the solution for smaller machines, for which the cost of CMS installation would exceed the budget for its maintenance but the use of wireless, portable, MEMS based sensors would allow to reduce the installation cost per each monitoring node by the factor of 10 (or even more while thinking about the mass production).

Acknowledgements:
The work presented in this paper was supported by funding from the research project co-financed by the KIC InnoEnergy Project Agreement number 32_2014_IP110_XSENSOR

References:

[1] Blanke, M., Kinnaert, M., Lunze, J., Staroswiecki, M., Diagnosis and fault tolerant control. Springer, Berlin, 2006, 2nd edition.

[2] Hameed Z., Ahn S.H., Cho Y.M., Practical aspects of a condition monitoring system for a wind turbine with emphasis on its design, system architecture, testing and installation. Renewable Energy vol. 5 issue 5:879-894, 2011, doi:10.1016/.renene.2009.10.031.

[3] Isermann R., Fault-Diagnosis Applications, Blackwell, 2011, London Book chapter.

[4] Milind A. Siddhpura, Arti M. Siddhpura, S.K. Bhave, Vibration as a parameter for monitoring the health of precision machine tools, ICDM-08, Coimbatore, India, February 01-02, 2008.

[5] Wang W., Tse P.W., Lee J., Remote machine maintenance system through In-ternet and mobile communication, International Journal of Advanced Manufacturing technology 31:783-789, 2007, doi:10.1007/s00170-005-0236-1.

[6] Albarbar A., Badri A., Jyoti K., Starr S., Performance evaluation of MEMS ac-celerometers, Measurement 42, 790–795, 2008, doi:10.1016/j.measurement.2008.12.002.

[7] Nagel DJ, Zaghloul ME., MEMS: micro technology, mega impact, IEEE Circuits and Dev Magazine vol. 17 issue 2, 2001, doi:10.1109/101.920875.

[8] Ratcliffe C., Heider D., Crane R., Krauthauser C., Yoon M.K., Gillespie J.W., Investigation into the use of low cost MEMS accelerometers for vibration based damage detection, Composite Structures 82, p. 61–70, 2007, doi:10.1016/j.compstruct.2006.11.012.

Bibliography:

[1] A. Muszyńska, Rotordynamics, Taylor & Francis Group, LLC, Minden (2005), USA.

[2] R.J. Patton, P.M. Frank, R.N. Clark (eds.), Issues of fault diagnosis for dynamic systems, Springer-Verlag, London (2000).

[3] M. Strączkiewicz, A. Jabłoński, T. Barszcz, Detection and classification of alarm threshold violation in condition monitoring systems working in highly varying operational conditions, Journal of Physics, Conference Series (2015), vol, 628, s. 012087-012087-B.