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Ultra low power wireless multi-sensor platform dedicated to machine tool condition monitoring

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Abstract

The H2020 PreCoM project aims at developing and deploying a predictive cognitive maintenance decision-support system for production equipment such as machine tools. The PreCoM system intends to identify and localize damage, predict its evolution, assess remaining lifetime, and increase in-service efficiency of machines by conducting preventive maintenance actions. In this PreCoM system, additional sensors are needed to gather measurements close to critical parts/tools in order to improve failure detection.

Commercial wireless sensor nodes are too restrictive regarding requirements for condition monitoring on industrial machine tools (50 g acceleration, 50 m long wireless range, several month lifetime, presence of cooling fluid and hot metal chips projection). Therefore, a dedicated wireless multi-sensor platform has been designed and developed in the frame of this project in order to provide additional measurements on highly moving parts, such as spindle head.

The PreCoM wireless sensor nodes are integrating a 50 g / 10 kHz - 3 axes accelerometer and a temperature sensor. They have been designed to be standalone devices with lifetime of around 1 year, and to fit all the machine tool environment requirements. The wireless sensor nodes are based on ultra-low power electronic devices and communication protocols to minimize their power consumption during all phases: sensing, communication and sleeping mode.

Those sensor nodes and their associated wireless platform have been successfully developed and tested in representative environment in laboratory, and then deployed on pilot machine tools within the PreCoM maintenance system.

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Keywords: Sensor node, wireless, condition monitoring, low power

1. Introduction

Industry has experienced three revolutions during the past 200 years, driven by mechanization, electrical power and the electronics & Information technology [1-3]. With the recent technology advance in Cyber Physical Systems (CPS), the Internet of Things (IoT) and the internet of Services (IoS) we are now starting the Fourth Industrial Revolution [4].

Cheaper and more powerful sensors, together with big data analytics, offer an unprecedented opportunity to track machine-

tool performance and health condition in the frame of this Fourth Industrial Revolution towards the Industry 4.0.

The Horizon H2020 PreCoM project (Predictive Cognitive Maintenance Decision Support System) aims to develop an innovative predictive maintenance system, that exploits the recent technology to enhance industries productivity by enabling damage identification, predict damage evolution and assess remaining asset life time. This system is based on four main functions: (1) data acquisition with embedded and external sensors, (2) artificial intelligence algorithms

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combining physical models, statistical models and machine-learning, (3) cloud-based production and maintenance planning and (4) human-interface-module including production dashboards and augmented reality interfaces for maintenance actions [5].

The PreCoM maintenance system efficiency highly depends on the reliability of the data to be processed: past data, production data, and physical data on the condition of the different equipments or assets. Therefore the sensors have to be located as close as possible of the critical parts (bearing, spindle head, etc.) to improve measurement reliability. As some critical parts cannot be connected with conventional wired sensors due to their high degree of movements (spindle head) or due to their localization, a wireless multi-sensor sensor platform has thus been developed and deployed in the frame of the PreCoM project to provide additional data on equipment and assets (vibration and temperature). Those new real-time measurements will be combined with production and maintenance data to enable this disruptive maintenance approach for damage localization and prediction.

2. Specifications for wireless condition monitoring

2.1. Selection of sensors adapted to condition monitoring

The type of sensor required for an effective condition monitoring (CM) system will depend on several factors such as the failure modes of the equipment/asset and the required accuracy to detect damage initiation, in order to be able to follow the development of a potential failure and predicting the “time to failure” [6,7]. Once the possible failure modes are identified as well as the necessary information needed to detect the development of these failure modes, appropriate sensors could then be selected and installed in the most appropriate location (as close as possible to critical parts).

There are many different sensors which can be used for monitoring the condition of manufacturing machines and processes, but they are not all equally informative [8]. The sensors that are the most relevant for monitoring manufacturing machines in detecting damage initiation and development are mainly vibration accelerometers and thermometers [9].

Temperature can be used as a complement parameter to vibration spectral analysis for condition monitoring. For example, it is beneficial to use temperature in addition to vibration on a shaft at a measuring point equipped with several identical rolling element bearings where it is necessary to distinguish the one with problems [10]. Vibration spectral analysis on its own may not provide the information required for identifying the damaged bearing easily.

2.2. Test site for the demonstration

The PreCoM System will be deployed in 3 different use cases: low volume manufacturing (SAKANA, General machining), high volume manufacturing (SPINEA, precision reduction gears) and continuous manufacturing (GOMACAMPS, pulp and paper), see figure 1. The PreCoM

project will exploit all the data collected from the machines in order to perform predictive maintenance in these 3 use cases.



Fig. 1. (a) use case 1 : Low volume manufacturing of wind power part manufacturing ; (b) use case 2 : High Volume manufacturing of precision reduction gears, (c) Continuous Manufacturing of Pulp and Paper.

In those different use cases, the most inaccessible and critical parts are: spindle heads of milling or boring machines and the creeping blade which removes the paper from the Yankee dryer in tissue paper specific machines.

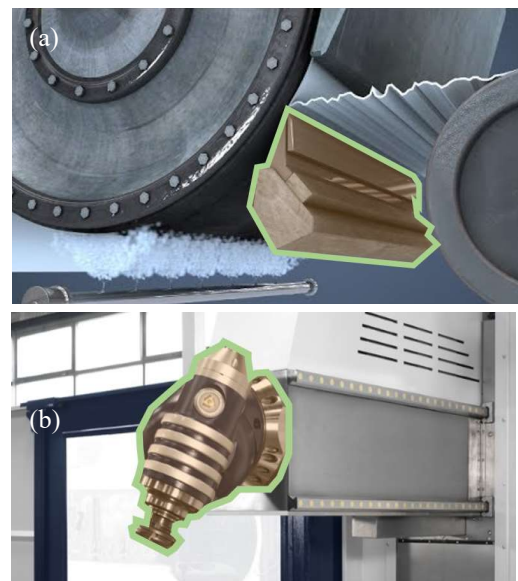


Fig. 2. (a) Illustration of the creeping blade and (b) of a highly moving spindle head.

Wireless sensor systems are interesting for these specific cases as it is always complicated to manage long cables towards the data acquisition system in industrial environments (creeping blade instrumentation) and highly moving parts (spindle head). Wireless sensor nodes will be integrated on those locations to detect failure initiation:

- Damage of gears in the spindle head due excessive to excessive operating conditions (high load)
- Degradation of the Yankee dryer due to excessive vibration of the creeping blade

2.3. Wireless Sensor specifications

To take into account environmental and applicative constrains for these 3 use cases (life time, communication range, dimensions, power consumption, and number of channels ...), the specification for the wireless sensor system has commonly been agreed with the end users, machine tool builders and maintenance experts. Those general specifications are listed in Table 2, and the technical specification for the sensors are listed in Table 3:

Table 1: Specifications for wireless sensors node.

Powering life time	Communication range	Size	Current consumption	Number of channels
> 1 yrs	> 10 m	< 10x10 cm ²	Sleep mode : 1-10 μA communication : 5-10 mA	1-3

One key specification is the life time of those sensor nodes, in order to be reliable and easily adopted by the end-users. To enable a long lifetime those sensors need to integrate ultra-low-power electronic components and to use ultra-low power communication protocols such as Bluetooth Low Energy (BLE).

Table 2. Specification for accelerometers and temperature sensor

Accelerometer	Range	Frequency	Sensitivity
	+/- 50 g	2 Hz - 10 kHz (+/- 3 dB)	100 mV / g
Temperature sensor	Range	Resolution	Type
	-50 + 120 °C	0.1 °C	PT100 or thermocouple

To obtain accurate vibration measurements, accelerometers should be mounted as close as possible to the component to monitor. Magnetic sensors that stick to the equipment will be used for the first tests, and stud mounts will be used for permanent installations. Stud mount is the best option to avoid dumping issues [11], but it requires drilling in the target material. For this reason, the end user and/or equipment manufacturer will be involved for further sensor integration tasks.

3. Wireless sensor platform

3.1. Reason for developing a dedicated PreCoM Wireless sensor Platform

Some industrial wireless sensors are already available on the market [12-15]. However, the system sizing, sampling frequency and expected lifetime of all those commercial sensor nodes are too restrictive regarding the PreCoM system requirements for condition monitoring in the different industrial use cases. Therefore, it has been decided to develop a specific sensor node and its wireless bridge to reach those challenging specifications.

Table 3. Comparison between available commercial sensor nodes

	Monnit		Lord	
	Vibration	Temperature	Vibration (G-link)	Temperature (TC-link)
Range Max	1.7 g	-40 + 125°C	40 g	-40 + 85°C
Sampling rate	1- 200 Hz	0.1 Hz	1 - 4 kHz	1 Hz
RF Frequency / Channels	433 to 900 MHz (4 ch)		2.4 GHz (16 ch.)	
Rx/Tx power consumption	25 to 35 mA (20 μA Sleeping)		5-10 mA (10 μA sleeping)	
Communication range	100 m		20 to 100 m	
Life time expected	few days (200 Hz during 5 s, /hour)	2 year (1 /hour)	2 weeks (200 Hz during 5 s, /hour)	5 year (1 /hour)
Package sizing cm ²	10 x 5	5 x 3	4.5 x 4.5	6 x 6

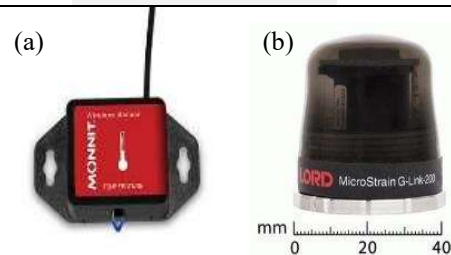


Fig. 3. Examples of existing wireless sensors: a- Temperature sensor (Monnit®), b - vibration sensors (LORD ®).

3.2. Architecture of the wireless sensor platform

The PreCoM wireless sensor platform integrates a 3 axis accelerometers and a temperature sensors to monitor spindle heads for milling/boring machines and Yankee blades for tissue paper machines. This platform is composed by up to four sensor nodes, a dedicated wireless bridge (called B.Leti) and a multiprotocol gateway from Savvy Data Systems (called Savvy Box). The wireless bridge is synchronized with the PLC/CNC automates via a ModBusTCP connection and collects the data from the sensor nodes. The Savvy Box gateway gathers the data from the wireless bridge via a FTP connection and send them to the PreCoM centralized server. The wireless sensor nodes are connected to the wireless bridge using the Bluetooth Low Energy (BLE) wireless communication protocol. This protocol has been selected as it allows a wide range of application: bandwidth up to 2 Mbit/s, communication distance of 50 to 100 m.

A representation of the architecture of the sensor IOT system is presented in the figure 4:

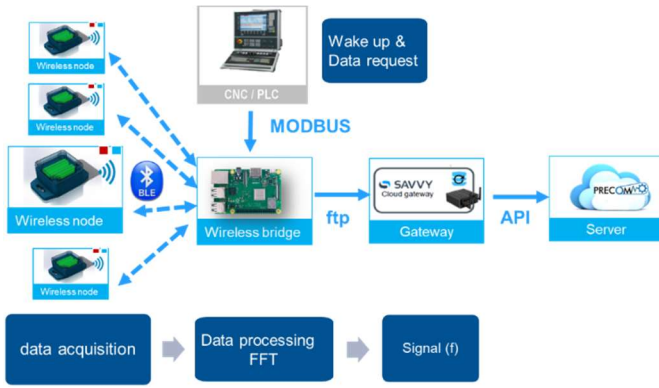


Fig. 4. Architecture of the wireless sensor node system

3.3. Hardware and software developments

3.3.1. Wireless sensor node electronics

The sensor nodes are designed to be long lasting standalone device with lifetime of around 1 year (60 sec measurements per day). Based on the previously described requirements, the electronic architecture of the sensor node has been defined. This architecture is shown in figure 5.

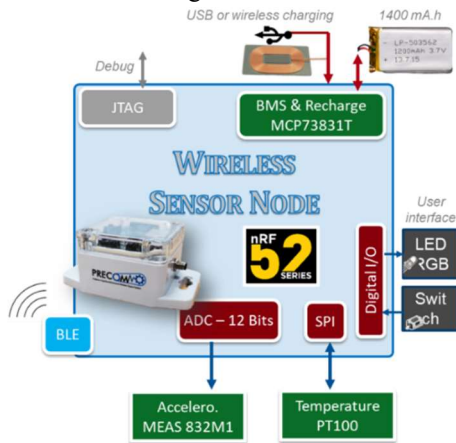


Fig. 5. Electronic architecture of the CEA/LETI wireless sensor node

The key component of the wireless sensor node is the nRF52840 System on Chip (SoC). This SoC is built around the 32-bit ARM® Cortex™-M4 CPU with floating point unit running at 64 MHz and it supports the Bluetooth 5.0 protocol. This SoC has exceptionally low energy consumption thanks to a sophisticated on-chip adaptive power management system.

The sensor node integrates a 50 g 3-axis accelerometer MEAS 832M1 (2 Hz to 10 kHz) and a PT100 temperature sensor IFM TS2229 TS-PT100. Those sensors have been selected regarding the sensor platform requirements (vibration, sensor resolution and power consumption).

The sensor node integrates 4 x 350 mA/h batteries to enable long lifetime in a quite small form factor (20x20x30* mm³). Those batteries represent an amount of energy of around 18 kJ, what is sufficient to process two slots of 30 s vibration measurements per day on more than one year using adapted components and power management.

To enable proper management of the batteries (charging, discharging), the node integrates a Microchip MCP73831 battery management system.

And finally, to allow long distance wireless communication in a highly constrained industrial environment (metallic moving parts, motor EM noise..), the sensor node integrates a dedicated 3D Antenna adapted to 2.4 GH communication (BLE) Antenova SRW009, which has a good radiation pattern isotropy.

3.3.2. Wireless sensor node firmware

The sensor node firmware is implemented in the NRF52 microcontroller. This firmware aims at configuring the Bluetooth Low Energy (BLE) as well as all the I/O needed for the sensors configuration/communication and the battery management. This firmware is based on the Software Development Kit 15.3 (SDK) integrating the proprietorial BLE libraries for the nRF52840.

3.3.2.1. Measurement management

When turned on, the sensor node turns immediately in sleep mode for minimizing its power consumption. Every second, the sensor node enters in advertising mode to verify if the *B.Leti* bridge is requesting a measurement. If not, it comes back to sleep mode, and if yes, it connects to the *B.leti* and proceeds to a set of measurement.

3.3.2.2. Battery management

The battery status of the sensor node is accessible by the *B.Leti* thanks to a Bluetooth dedicated service and is visible on a LED HMI if a recharge is requested. The battery charge level and corresponding voltage is described in the table below:

Table 4. Battery level status

Battery voltage [V]	Status [%]
$V > 4.1$	100
$3.7 \leq V < 4.1$	75
$3.3 \leq V < 3.7$	25
$V < 3.3$	0

If the battery voltage is lower than 3.3 V, the sensor node is turned to a mode of minimal power consumption and no more measurements can be performed. In this case, a red LED is flashing for a period of one minute to indicate that the node must be absolutely charged.

The battery charging is allowed through either USB or any QI type inductive charger. Battery charging is allowed at any time during the life cycle of the sensor node except during a measurement phase. When charging, the node is put in OFF mode. Once the node is fully loaded and/or the charger is removed, the node resets and starts again in the normal operating cycle.

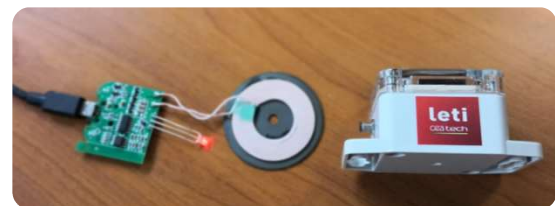


Fig. 6. Wireless inductive charging of the sensor node

3.3.3. Wireless Bridge software implementation

The *B.Leti* wireless bridge is used to process orders coming from the ModBusTCP interface, relaying them to the wireless acquisition device using BLE, and to provide the acquired data on a FTP server. To improve flexibility, this bridge has been implemented on an embedded Linux Micro Computer raspberry Pi3B+ (compatible with Bluetooth Low Energy) and can be implemented on any Linux environment. The functional architecture of the wireless bridge is described on the figure below:

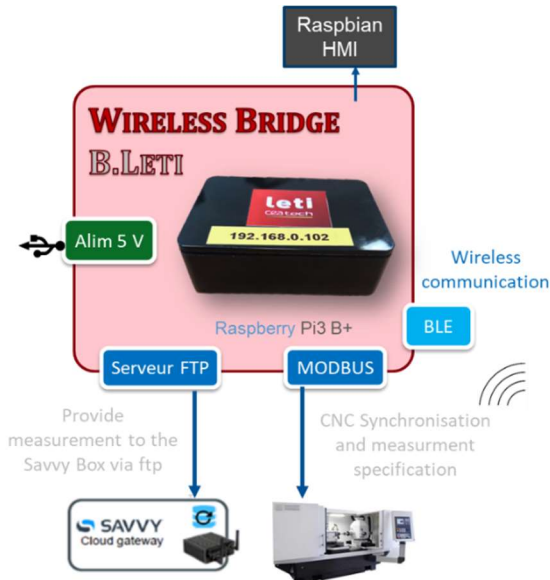


Fig. 7. Functional architecture of the CEA/LETI wireless bridge.

Once the *B.Leti* is properly configured, the physical setup can run without any human interaction.

4. Wireless sensor platform tests and validations

Preliminary tests have been set up to evaluate communication quality in a harsh environment, determine sensor node power consumption, and validate acceleration measurements.

The power consumption of the sensor node has been measured in CEA/LETI laboratory. The power consumption in sleep mode is below 10 μ W, the data processing and communication mode is in the range of 10 to 15 mW during 60 to 80 s per day for the defined usage. Taking this power consumption into account, the life time of the node is expected to be more than 1 year. Long duration tests are in process.

The operation of the wireless communication has been validated in an industrial shop floor environment in collaboration with DANOBATGROUP and IDEKO, see figure 7. The communication range reached 30 m, even with shadowing of metallic tools and machines. Moreover, as soon as the connection is established between the sensor nodes and the *B.Leti* wireless bridge no data packets are lost thanks to Bluetooth protocol resilience. The wireless data transfer speed rate reached up to 180 kbits/s; and the RSSI (Received Signal Strength Indication) is in the range of -40 to -90 dB for 1 to 30 m distance in this shop floor environment.

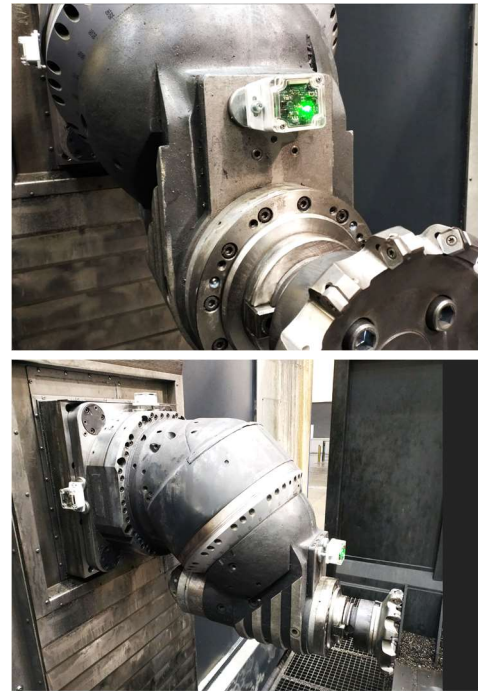


Fig. 8. Wireless communication tests and validation at SORALUCE/IDEKO

The full operation of the sensor nodes have been tested and validated at the IWB of the Technical University of Munich shop floor. Examples of measurements with a Kistler reference accelerometer and a PreCoM wireless sensor node working at 10 kHz sampling frequency are illustrated in figure 9.

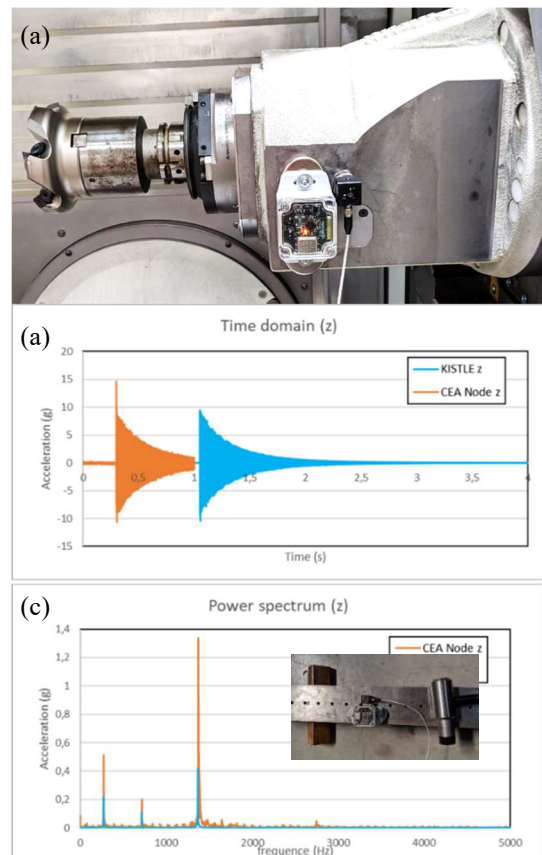


Fig. 9. (a) Functional test at TUM facilities and (b) Comparison between a Kistler reference accelerometer and CEA/LETI wireless sensor node working at 10 kHz sampling frequency (hammer qualification test)

5. Conclusions and perspectives

A dedicated wireless multi-sensor platform has been designed and developed in the frame of the PreCoM project in order to provide additional measurements for inaccessible critical parts, such as the spindle head in milling machines or creeping blade for paper mill. This platform is composed by wireless sensor nodes and an associated wireless bridge to provide measurement data to an external data server.

The wireless sensor nodes are integrating a 50 g / 10 kHz – 3-axes accelerometer and a temperature sensor as those two sensors are the most suitable for condition monitoring of machine tools. They have been designed to be compatible with machine tool environments and have a lifetime of around 1 year. The sensor nodes are based on ultra-low power electronic devices and communication protocols to minimize their power consumption during all phases: sensing, communication and sleeping mode.

Those sensor nodes have been successfully tested in representative environments in laboratory, and then deployed on pilot machine tools to provide additional condition monitoring data to the PreCoM predictive maintenance system.

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