Innovative smart sensors to enhance eco-efficiency of a continuous (steel) production line

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Abstract

The paper aims to demonstrate the benefits for a global approach that allows to define new research directions, new potential industrial markets, and increasing interest from potential users.

Combining performance, economic and environmental criteria in a joint assessment approach for the target applications of sensor systems, facilitates significantly the communication between service provider and user. The environmental assessment approach for sensor systems will be available as a beta-version online tool tentatively from July 2013 onwards. Interested SMEs are invited to get involved as the LCA to go consortium will provide also a comprehensive mentoring for SMEs.

Key words: Smart sensor, Assembly, Monitoring, Life Cycle assessment, Carbon foot print.

Introduction

Due to continuous cost reduction, increased functionality and extended reliability of microelectronic in general, the microelectronic based sensors penetrate the application areas where before only bulky and discrete system was used. An example of such application is temperature monitoring at harsh environment. Despite the described progress, there is no standard platform to design such monitoring system. To ensure the best value for the customer the total value chain (see figure hereunder) must be considered carefully.

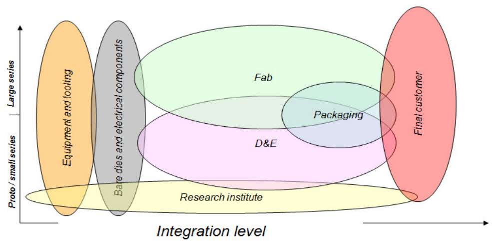

Fig. 1: Chain of Values for a smart sensor application.

TAMMI (micro-multi-sensor-platform)

The majority of industrial companies which have continuous production plant have to manage the amount of Euro they spend every minutes and what are the actions to save or even earn money (by saving energy, increasing efficiency of the production line,…). Therefore it becomes evident that companies have to control how their equipments are used and when that equipment will fail.

It is well known that sensor systems are employed in industrial applications for condition monitoring and/or process control with the intention of a more efficient, predictive maintenance and avoidance of non-optimal process conditions.

Unfortunately, no standard exists as every production plant is different. That means that they are obliged to make curative maintenance instead of a real health monitoring maintenance allowing to anticipate the problems.

In response to such challenges, Taipro Engineering developed and demonstrated a micro-multi-sensor-platform, named TAMMI (figures 2), which can be quickly adapted to the measurement needed by a wide range of end-users.

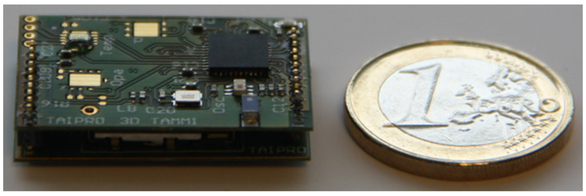

Fig. 2: TAMMI sensor node platform.

The platform is a development tool for rapid integration of different existing bare die sensors in one miniaturized (5cm³) device. The TAMMI performances can be summarised as follow:

- Autonomous multi-sensor microsystem
- Open tool box easily adapted to the application
- Easy to install (drag & drop)
- Up to 5 sensors in a 5cm³ microsystem:
  - Temperature
  - Pressure
  - Acceleration, vibration, inclination, tilt, shock
  - Sound
- 5 sensors can be chosen from a list (on demand)
- Customized solution possible
- ZigBee wireless communication
- Autonomy: up to 150 days with 2 AA batteries
- Integrated memory capacity up to 32GB to store measurement data
- Integrated real time clock.

The objectives of such a platform are to allow:

- To process parameters monitoring
- To monitor mobile equipment like bridge cranes, ball bearings, rotating tools
- To perform health monitoring of civil engineering structures like bridges, dams
- To be used as a tools using time recording
- To monitor temperature in industrial fridges, oven, trucks (perishable goods)
- Shock/vibrations monitoring on equipments, goods during transport, and etc.

The ready to use TAMMI smart sensors can be summarized as in the figure below

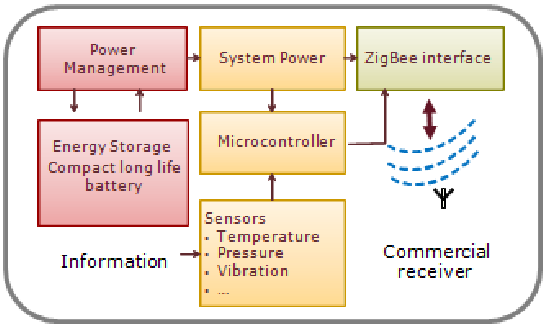

Fig 3: TAMMI working principles

This tool was developed in particular on an evident request and need from steel production to identify some deviation on the production which can lead to catastrophic huge cost (stop of the production plan, lost of production material, lost of efficiency and etc.).

Link between TAMMI and AMM

This platform (TAMMI) is designed and constructed in such way, that it respects compatibility of all components and system features on board, aware of future needs for autonomy, harsh environment, ultra miniaturization. TAMMI is supported by Micro-platform for Multi-sensors (AMM) developed by Microsys laboratory, University of Liege. The AMM is a development platform for sensing, transmission and processing a wide range of external signals, the platform includes a concept, a design and software. TAMMI addresses immediate customer needs, whereas AMM is targeting long-term applications, up to 5-10 years from now. Close link TAMMI to AMM ensures further system miniaturization and truly autonomous features. AMM provides the opportunity to extend the operational window of the smart sensor from standard environment to harsh environment. This was almost impossible due to specific restrictions dictated by microelectronics before.

Autonomous Micro-platform for Multi-sensors (AMM) for wireless monitoring

Using this platform, two specific applications have been developed: (i) a monitoring system for standard environmental conditions and (ii) a microsystem for harsh environment.

Standard environmental conditions

A combination of solar cells is used to reach the wanted voltage and power. The output power measured under a light intensity of about 50 000 lux can reach up to 12.8 mW. The solar cells placement is made in accordance with the components location to provide some flexibility to the system (bend radius ~ 50 mm). The thinfilm battery is slightly flexible as well. The microsystem is configured with a sampling period of 60 s and a size of the data of 4 bytes (1 for the temperature, 2 for the light intensity and 1 for the ID number). In this case, the mean power integrated over a period is measured using a shunt and an oscilloscope: P_{cons} = 9.2 µW and P_{cons} = 13.9 µW with a RF power of 1 dBm and 11 dBm respectively. The battery capacity of 1mAh is then sufficient to supply alone the system during 4 days.

The array of tiny solar cells (lateral dimension of 2.5 x 5 mm^2) is mounted on a flexible PCB. The cathode is mounted with conductive paste whereas the anode is connected to the PCB by wire bonding (figure 4).

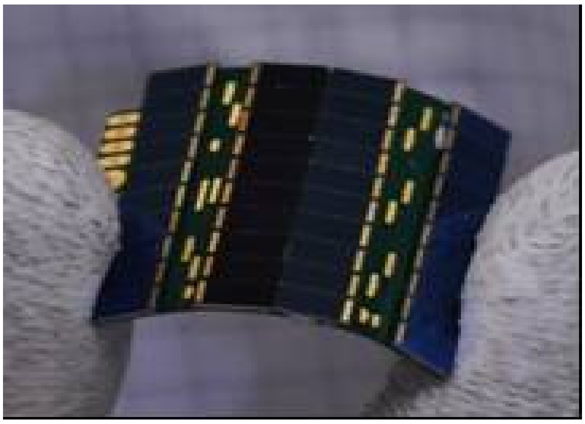

Fig. 4: Array of solar cells mounted on a flexible PCB to harvest energy from ambient light.

The Al wires of 25 µm diameter are protected by dispensing UV encapsulant. In standard configuration, the battery, the electronics and the solar cells are stacked and connected together. The whole stacking is flat and slightly flexible. To conserve flexibility, an elastic and transparent material is used to protect the microsystem while leaving the light hitting the solar cells. In practice, the assembly is placed in the middle of a closed mould where a siloxane material (PDMS) is injected. After removal from the mould, the AMM node is ready to work alone or in a wireless sensors network (see figure 5).

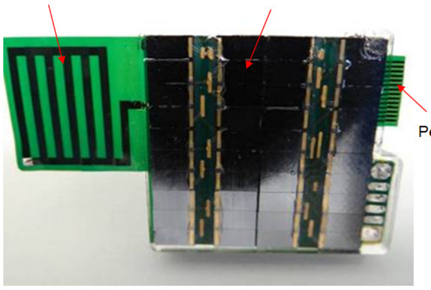

Fig. 5: AMM encapsulated in PDMS for standard conditions.

Thanks to the elasticity of PDMS, the whole packaged microsystem can still adopt slightly curved surfaces (bend radius ~ 100 mm).

The antenna is directly printed on the flexible PCB. The frequency choice of 868 MHz is made from a trade-off between the antenna size, and the antenna span for a given output power. The Standing Wave Ration (SWR) parameter has been measured for 3 bespoke designs and 1 commercial antenna. An ideal transmission line would have a SWR of 1. We have obtained SWR = 1.3 for the best antenna design whereas the commercial antenna presents a SWR = 2.2. As a result, the RF communication of the AMM is particularly efficient, which leads to a good functioning with the lowest transmission power (+1 dBm). Indoors, the antenna range is typically 10 m due to obstacles, whereas outdoors it exceeds 100 m. There is a possibility to extend the antenna span by using an output power larger than 1 dBm.

High temperature application

First of all, we checked the possibility to power the microsystem by a thermoelectric generator. As explained, the heat flux direction is inverted between the heating and the cooling phase. That means the minimum output voltage must exceed the start up voltage of the dc/dc converter, added to the threshold voltage of the diodes. In practice, this target value cannot be reached because the copper box deflects the heat flux from the TEG.

As a result of that, we decided to power the microsystem using an AC magnetic field. Practically, a 2D coil has been realized on a flex substrate and locked in the box, with the electronics. The box walls are made from a copper sheet, see below. It is essential to overcome the Eddy currents appearing in the copper walls of the box. From calculation, we found that the frequency of 400 kHz leads to the higher induced voltage. This result was confirmed by experimentation. A large coil made of copper wire is used to generate a large magnetic field, combined with the fitted capacitor. Finally, a full battery charge can be achieved successfully with this technique.

The material used to build a protective case must have an excellent thermal conductivity and sustain 800°C. Copper was selected in view of its good mechanical properties and a reasonable price. In addition, Electron Beam Welding (EBW) has been carried out successfully to create a hermetic soldering.

Practically, a 0.2 mm copper sheet is embossed with 16 cavities in order to create a batch of packaged AMM in one shot (see figure 6).

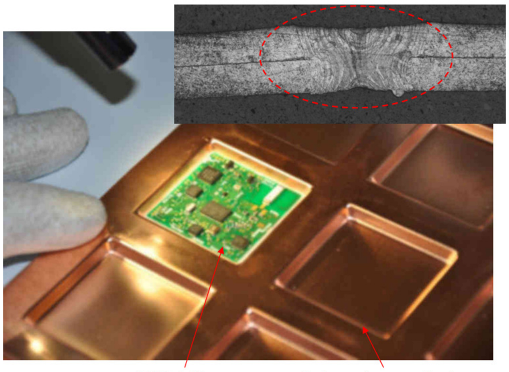

Fig. 6: AMM assembly for high temperature applications, micrograph of the welding between two copper sheets for hermetic sealing is in inset.

Each cavity is successively filled with insulating material, AMM platform, and insulating material again. Then a flat copper sheet is placed over the whole assembly and is mechanically clamped before to start the EBW operation. As this welding technology involves evacuating air, vacuum is inside the hermetic box, which leads to enhanced performance of the insulating material. The hermeticity of the sealing has been examined, and the sealing is gross leak tight. In fact, deflection of the walls is observed when the pressure in the chamber goes back to the atmosphere pressure.

As for the insulating material, specimens have been thermally characterized in the following conditions: vacuum of less than 1 mbar and with a uniform load of 100 kN/m². The required material is synthesized by the chemistry department of the University of Liege. The measured thermal diffusivity on this tailored material is only 0.04 mm²/s, which is 6 times lower than the best commercial product tested.

From the geometry and material selection, the Quickfield® software has been used to estimate the temperature rise in the platform. A convection boundary condition is imposed at the top surface (convective heat transfer coefficient h = 10000 W/(m².K)). Figure 7 depicts the temperature distribution after 3 seconds and illustrates how the heat is drained by the copper walls.

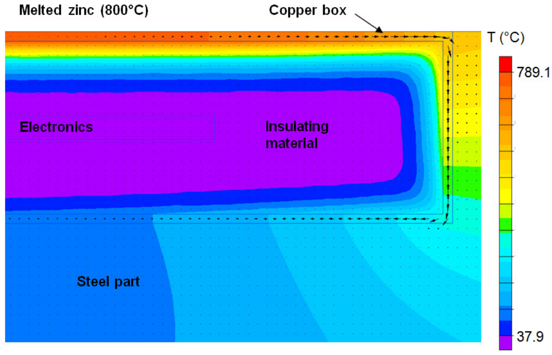

Fig. 7: Modelled temperature distribution in transient heat observed after 3 seconds. The heat flux is represented by arrows.

This configuration leads to a temperature increase seen by the electronic board of only 17.9°C. In order to validate the theoretical calculation we prepared a test plan, there on the first stage we will subject the system to boiling oil environment, on the final stage we will investigate it the molten Zn.

Approach to analyze a positive effect of sensor network like TAMMI

The environmental impacts of sensors and sensor networks have been analyzed in the past [1, 2, 3], but what was still missing, is a transparent way of quantifying the positive effects a sensor network might bring about in a given application scenario. This is the much more important effect, when applying sensors for monitoring, control and automation in energy-intensive industries, such as steel production, paper production, printing, polymer extrusion, glass production, automotive assembly and other automated production lines, through-feed oven processes (e.g. in ceramics production and processing) or semiconductor manufacturing.

The following effects are relevant:

(1) Reduced downtimes through condition monitoring and predictive maintenance, and related effects on energy and auxiliaries consumption

(2) Efficiency monitoring: detection of wear and tear long before a failure will occur, but when already the energy efficiency of a drive, pump or the like is affected

(3) Improved process performance and efficiency due to higher machining speed through (sensor-based) process automation

(4) Improved product quality through process monitoring

(5) Reduced yield losses through process monitoring

(6) Optimized (i.e. reduced) auxiliaries dosing through process monitoring

The approach links all relevant material and energy flows of the industrial processes, which are influenced directly or indirectly by monitoring and control, with environmental impacts (resource consumption, greenhouse gas emissions). The scenario analysis allows a direct forecast of likely environmental savings, which along with economic data facilitates the communication of the advantages of a sensor system.

The energy savings and other environmental and cost advantages will typically not be realized through the sensor system directly (although in some cases a direct autarkic process adaptation is thinkable), but through the transparency created: Consequently, company internally decisions have to be made and corrective actions to be taken, using internal software tools and workflows. This difference of using LCA to go in the project planning phase versus the activities which follow in the process operation phase are depicted in figure 8.

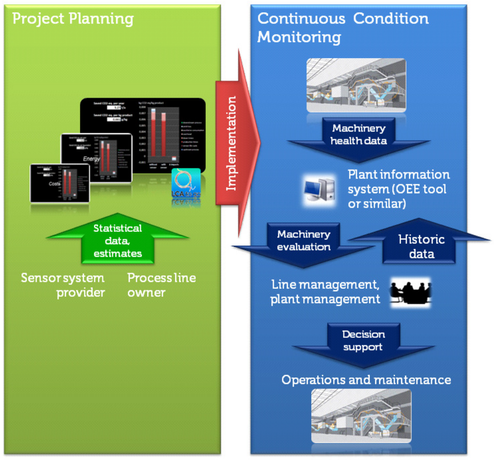

Fig. 8: Application scenario LCA to go for project planning.

The dominant environmental benefits realized through better line monitoring are assumed to be reduced downtimes, and thus higher production and energy efficiency of the line, and the reduction of yield losses. The forecast of downtime scenarios requires some assumptions about the likely impacts of any such interruption. For example, if the downtime of rolling mills is short, the previous processes (casting, steelmaking) are not affected because the storage capacity for the steel arriving for rolling is not exhausted. Following table shows exemplarily how the reduction of unattended downtimes of the rolling mills due to the sensor solutions may reduce the effects on the previous production processes and, therefore, save energy and reduce environmental impacts.

Table 1: Downtime escalation scenarios (fictional entries)

Time of unattended downtime of the rolling mills	> 5 minutes	> 5 minutes < 20 minutes	> 20 minutes < 2 hours	> 2 hours
Impact on the previous processes	None	Casting must be stopped	BOS, EAF and casting must be stopped	Blast furnace, BOS, EAF and casting must be stopped
Occurrence per year without sensor system	100 times	10 times	0.2 times	0.1 times
Occurrence per year with sensor system (fictional scenario)	40 times	5 times	0.1 times	0.01 times

Environmental Screening Results

A first estimate based on the calculation model developed in LCA to go indicates a potential for greenhouse gas savings in the range of several thousand tons of CO_2 emissions per year, mainly attributed to an expected reduction in yield loss: In this case the methodological approach considers the embedded energy and greenhouse gas emissions of the steel, which is partly lost when yield losses have to be returned to upstream steel smelting processes. Yield loss reduction effect can be in the range of 3,000 t CO_2-eq. reduction annually in terms of greenhouse gas emissions, which equals the carbon footprint of 230 households in Germany. Absolute energy consumption of a production line (and thus indirect greenhouse gas emissions) is higher with the sensor system in place due to an increase in productive time. From a productivity perspective, i.e. per mass of product output, electricity related greenhouse gas emissions of the production line per kg steel output go down. Such findings and calculations significantly enhance the communication between sensor system provider and his client, and help to unveil the likely benefits of a sensor solution.

The screening results demonstrate also that the production of the sensor nodes as such in this scenario has a marginal impact compared to the likely savings, and is easily outweighed not only by the anticipated yield loss reduction, but also regarding energy efficiency increase due to reduced downtimes.

Conclusion

The paper demonstrates the benefits for such global approach that allows to define new research directions, new potential industrial markets, and increasing interest from potential users.

Combining performance, economic and environmental criteria in a joint assessment approach for the target applications of sensor systems, facilitates significantly the communication between service provider and user. The environmental assessment approach for sensor systems will be available as a beta-version online tool tentatively from July 2013 onwards. Interested SMEs are invited to get involved as the LCA to go consortium will provide also a comprehensive mentoring for SMEs.

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