Electronic Sensor Nodes Powered over Fibre Optimized for Ultra-Precise Temperature Measurements in Magneticresonance Imaging Machines

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Summary: Sensorial materials are fundamental for new intelligent products. Implementing sensorial functions and local data processing capabilities into the materials will lead to intelligent products that can "feel" and "judge" and therefore interact with other systems, human users and the environment, contributing to our efforts towards energy savings, safety and security, mobility, and health.

To realize this vision, the DFKI, with other national industrial and scientific, is developing intelligent sensor nodes connected by optical fibres in a large-scale sensor network. In contrast to other wired or wireless sensor networks, both a high-speed data link *and* power supply are realized via an optical fibre. This makes batteries or other local energy sources for the sensor nodes superfluous and the network immune against strong electro-magnetic influences, which are typical for harsh industrial environments or some medical applications like magnetic resonance imaging. In addition, the lack of a local energy source reduces significantly the sensor node's size and makes it completely maintenance-free which is a key aspect for the integration into new materials.

The paper briefly describes the general idea of ultra-low power electronic sensor nodes and the joint transmission of data and power over optical fibres as well as its realization. As an example, a first industrial application is presented, making use of the system's electro-magnetic immunity for highly precise multi-channel temperature and acceleration measurements in magnetic resonance imaging machines. In addition, the key factors for achieving a greater flexibility compared to classical fibre optic sensor networks are pointed out.

Keywords: Material, Network, Sensor, Temperature.

1. Motivation

For future intelligent products and systems, sensorial materials are needed for the detection of human or environmental interactions and events. Today, the manufacturers of most sensorial materials are using a "hybrid integration" process [12]. Only after the separated production of the sensors and the raw material, the sensors are embedded into the material. But embedding the sensorial functionality into the material is only one step towards intelligent materials, because "local processing of the sensor signals and facilities to derive meaning from them" is also necessary to "base decisions on it" [11].

Since 2010, the DFKI develops intelligent sensor nodes with several other partners at the University of Bremen and national industrial partners. The core idea bases on electronic sensor nodes connected by optical fibres in a large-scale sensor network. In order to make the sensor network completely maintenance free, which is a key factor for the integration into materials, both a high-speed data link and power supply are realized via the optical fibres. This makes local energy sources for the sensor nodes superfluous.

The advantages of the presented sensor network compared to classical Fibre Bragg grating (FBG) sensors concerning the integration into composite materials like glass or carbon fibre-reinforced plastics (GFRP, CFRP) have already been discussed in recent publications [4]. Especially the need for a central processing unit which cannot be integrated into the material limits the use of the FBG sensors. In addition, possible applications like structure health and condition monitoring of rotor blades for wind energy plants have been presented.

This publication focusses on temperature monitoring applications in high electro-magnetic fields around three Tesla, typical for modern magnetic resonance imaging (MRI) machines used to visualize internal structures inside the body. It is structured as follows: firstly a brief overview of state-of-the-art temperature measurement techniques in MRI machines is given and the need for precise measurement devices is explained; secondly the technical realization of the electronic sensor nodes and their optical interconnection is presented.

2. Introduction to medical thermography and common measurement systems for the use in MRI machines

2.1. Thermography in medical applications

The interest in local asymmetrical temperature changes in the human body goes back in medical history to Hippokrates[16].Today, thermography has reached practical relevance in the areas of natural contraception[5, 15], the diagnosis of certain diseases which are associated with qualitative and quantitative changes of skin temperature[7, 8], as well as pain diagnosis [9, 14, 17].

The methods used to assess temperature of the human body differ depending on the application. In the medical daily business as well as in many clinical studies, one of the main questions is to find the best possibility to measure the so-called core temperature. ISO 9886 refers to the term "core" as all the tissue which is situated deep enough in order not to be influenced by the temperature gradient of the body's surface. Therefore, the term "core" cannot denominate one specific place inside the body and the body's inside cannot have one single temperature everywhere. Consequently, there is more than one measure for the core temperature [6]. Depending on the design of a study and the thermometers used, the temperature of the hypothalamus [5], rectal, or oral temperatures are seen as the best measures of core temperature [2]. In order to measure brain temperature, infrared ear thermometers are used based on the hypothesis that the tympanic membrane reflects brain temperature.

Fast temperature changes can be better collected via the measurement of ear temperature. Oral and especially rectal temperature changes are much more inertial [2].In addition to the need of thermometers providing a fast response and high accuracy, automatic measurements must be possible to enable remote sampling within the MRI machine. Actually, samples are often only taken before and after the MRI scan [3].

2.2. Common temperature measurement systems for MRI machines

Most temperature sensors which are frequently used in commercial and industrial applications are not suited for use in MRI machines because of the strong electro-magnetic fields. For example thermistors typically contain a nickel barrier making the sensor magnetic. This causes movements of the sensor within the magnetic field and produces artefacts in the MRI, especially effacements around the sensor. Resistance thermometers have typically low sensitivity resulting in a bad signal-to-noise ratio of the analogue output signal.

To overcome the problems of the strong magnetic fields, fibre optic sensors are typically used for MRI measurements. They mainly base on Fabry-Pérot interferometers using optical resonators as sensing elements. The optical resonator consists of two partly-mirrored fibres with different temperature coefficients of expansion within a glass cavity (figure 1). Although the Fabry-Pérot temperature sensors are completely immune to magnetic fields, the class cavities are very fragile and the measurement system typically costs several thousand Euros.

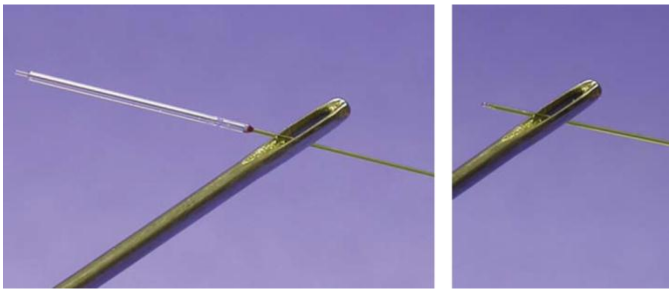

Figure 1. Examples of commercially available Fabry-Pérot temperature sensors with 800µm diameter (left) and 210µm (right) [13] from FISO Technologies Inc.

3. Technical realization of the electronic sensor nodes

Figure 2 shows an overview of the different modules within an electronic sensor node. This structure was originally developed for electronic sensor nodes which should be embedded into composite materials, measuring physical values like the temperature distribution or strain gradients. The optoelectric transducer, the energy management and the microcontroller are generic for all applications, only the sensors are application specific. This guarantees a fast development and short time-to-market even for very specific measurement scenarios. This structure was also used and only slightly adapted for the sensor device in the MRI machine.

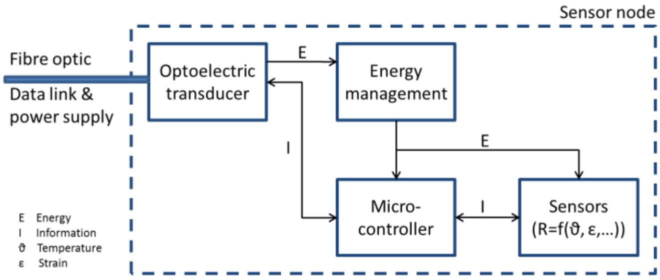

Figure 2. Block diagram of the sensor device.

3.1. Optoelectric transducer

The reception part of the Optoelectric transducer consists of two photodiodes with different peak wavelength sensitivities. The power photodiode is connected directly to the energy management, whereas the data photodiode is linked to the microcontroller by a trans impedance amplifier increasing the possible communication bandwidth. The system has been tested with up to 115200 baud. A further increase can be achieved by changing the settings of the trans impedance amplifier, but will result in higher energy consumption. For most sensorial applications, the attained bandwidth should be sufficient. For the data transmission, a simple LED is used.

3.2. Energy management

The maximum open circuit voltage of silicon photodiodes is in the range of 0.6V and the maximum power point is typically located between 0.3 and 0.4V. Therefore, a step-up converter has to be used to generate the supply voltage for the microcontroller and the sensors. A highly integrated step-up converter and power manager (LTC3108) from Linear Technology has been chosen which operates with voltages as low as 20mV and generates multiple user selectable output voltages. As the microcontroller and the sensors are in different sleep modes most of the time, redundant energy is stored in the output reservoir capacitors and used for the typically short wake-up periods, when the microcontroller and the sensors are active.

3.3. Microcontroller

For the electronic sensor nodes, a rather powerful 32bit microcontroller based on an ARM Cortex-M3 core from Energy Micro's EFM32 ultra-low power microcontroller family was chosen to permit a flexible data (pre-) processing on the sensor node. Simulations [1] during the design phase proved that the overall energy budget is advantageous if more energy is used for the microcontroller's processing of the sensor information than transmitting the larger raw data packets.

3.4. Sensors

To allow flexible measurement scenarios, sixteen temperature sensor channels have been implemented as well as a three-axial acceleration sensor. The acceleration sensor detects the MRI machine's vibrations during the different MRI scans, caused by the MRI's coils' expansion and contraction due to the Lorentz force. The information can be used to synchronize the sampled temperature values even without external trigger signals. To each temperature sensor channel, a single digital temperature sensor can be connected. Each calibrated sensor can achieve an accuracy of ±0.07°C in the range of 25 to 45°C and a resolution of 4mK. A read out of all sixteen channels takes about 200ms in order to guarantee a quasi-simultaneous measurement. The sensors are packaged in a tiny plastic insulation preventing the sensor element from being crushed by people stepping on them.

3.5. Base station and PC application

The base station can be connected via USB to a PC outside the MRI suite and is also powered via USB. For the optical connection of the base station and the sensor device, commercial polymer optical fibres with FSMA connectors are used. The base station provides the optical power for the sensor device and reads out the temperature and acceleration data. In addition, configuration settings like the measurement interval can be transmitted to the sensor device. An external trigger input allows the synchronization with the MRI machine, allowing a more exact timing than the acceleration information although this wiring takes more time during the measurement set-up.

A simple PC application is used for the communication with the base station and saves the received temperature and acceleration values in a comma-separated values CSV file in plain-text form. In addition, the sample frequency can be adjusted and individual threshold values can be set to alarm the user if specific temperature levels are exceeded. This is important, as especially MRI machines with very strong magnetic fields of 7 Tesla and above cause a significant warming of the patient within the machine which is only allowed in strict limits.

4. Conclusion

Although the temperature measurement in MRI machines is not dealing directly with integrated sensor nodes, it is a good example for the sensor network’s great flexibility and its easy adaptability to new applications. This is achieved by the use of electronic sensor nodes with embedded microcontrollers and standardized communication interfaces. Only the sensor elements themselves need to be adapted to the new scenario reducing the development costs and the time-to-market for new intelligent products. In comparison to frequently used fibre optical measurement systems like Fabry-Pérot interferometers, a more precise, cost effective and robust multi-channel measurement system has been developed.

As the basic sensor network structure can be easily adapted to other applications, other scenarios are possible as well. Especially the optical interconnection makes the network perfect for harsh industrial conditions, like explosive or chemically aggressive environments or strong electro-magnetic fields.

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