Industrial Bluetooth Wireless Sensor – Hardware Considerations

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***Abstract* - The industrial environment implies harsh constrains when it comes to gathering data form sensors and storing or displaying it. Eliminating the cabled connection between a sensor and a display/memory unit enhances the performances and the manageability of a sensor system. This paper describes the practical considerations that led to the design of a small-sized, low-cost industrial wireless sensor based on the Bluetooth wireless communication standard.**

I. Introduction

There are obvious advantages in having a wireless link between a sensing unit and the display or memory unit within a data acquisition system: the lack of transmission cable allows a much more larger application field, improved manageability and, assuming an error-free wireless transmission, higher perturbation immunity, hence higher accuracy. Furthermore, the physical design is more simple and cheap without the need of expensive plugs and isolations.

The main disadvantage of a wireless sensor is the need for an autonomous portable power source (battery), a key issue in the context of the design of a small-sized sensor unit. Extensive research was done in finding the right balance between the size and the capacity of the battery and its optimal exploitation in generating the various voltages needed for powering the sensor itself together with the additional circuitry.

The second disadvantage of a wireless design approach for a sensor system is the limited bandwidth of the wireless channel that imposed restrictions on the sampling frequency and on the resolution with which data is acquired from the sensor.

The physical design was based on an existing cabled industrial hand-held sensor with a strain-gauge transducer, the challenge being to integrate at minimum costs all electronic circuitry, together with the power supply and the Bluetooth radio unit, in the original sensor housing with a rectangular section of 35 x 25 mm. A PDA (Personal Digital Assistant) with Bluetooth interface was used as main display and memory unit, and test have been done also using a Laptop/Desktop PC with a Bluetooth adapter.

II. Bluetooth

With the restriction of a low-cost design, the number of suitable standards which could be used for the wireless communication was reduced to practically three choices: ZigBee (IEEE 802.15.4), Wireless LAN (IEEE 802.11) and Bluetooth (IEEE 7802.15.1).

The first standard, ZigBee, is in fact specially designed for sensor and automation application, with very low power consumption but also with relatively low data rates (less than 250 kbps). This first inconvenience together with the limited availability of ZigBee modules and adapters on the market led to the early dismissal of this standard.

Wireless LAN (WLAN) is a robust standard with very good throughoutput (11 Mbit/s in the most popular version, IEEE 802.11b) and extensive coverage. Unfortunately this standard was not originally designed for low power consumption, a typical WLAN module drawing from 200 mA to 400 mA, which is unacceptable for small-size batteries with a capacity up to 800 mAh. Furthermore, the cost of WLAN modules is higher than similar Bluetooth modules.

Bluetooth is a radio standard primarily designed for low power consumption, with a short range (power class dependent: 10 centimeters, 10 meters, 100 meters) using low-cost transceiver microchips. The power consumption of a Bluetooth module varies between 10 mA and 70 mA depending on configuration and power class. For the version 1.1 of the Bluetooth standard the throughoutput is maximum 723.2 kbps at an asymmetric link and 433.9 at a symmetric link, acceptable values for the set purpose.

The Bluetooth Protocol Stack offers a variety of so-called profiles, which define the possible applications. Among the profiles adopted by the Bluetooth SIG (Special Interest Group) are: Dial Up Networking, Audio Gateway, Generic Access, Headset and Serial Port Profile (SPP). The last profile is a very useful feature that allows a Bluetooth device to act as a virtual transparent serial interface compatible to the classic PC serial interface. On hardware level, the Serial Port Profile is contained in the RFCOMM layer of the Bluetooth Protocol Stack having a 9-wire typical serial interface. This standard serial interface is very easy to implement and interconnect with other hardware such as serial A/D converters and microcontrollers.

Based on the above-mentioned considerations, Bluetooth was chosen as the communication standard for the wireless sensor. The large amount of Bluetooth devices and built-in interfaces for PDAs, Laptops and even mobile phones existing on the market was another additional point for this choice.

The Bluetooth modules that have implemented only the SPP Profile are called "Cable Replacement" modules and can be found on the market in various sizes and prices based mainly on transceiver chips from CSR, Infineon (former Ericsson Microelectronics) and National Semiconductors.

The first prototype of the wireless sensor used a Bluetooth Module built by Connect Blue (Sweden) based on an Infineon transceiver. The module was a Class 2 transceiver (range 10 m), featured an on-board ceramic antenna, both RS232 and UART communication interfaces for some 80 $.

The module used in the second prototype was built by Amber Wireless (Germany) using a National Semiconductors Bluetooth transceiver chip, the LMX9820. The price for a module with on-board antenna was 40$ and 70$ for one with external antenna. Both delivered very good results in terms of power consumption, reliability and range of the wireless transmission. Furthermore, the reduced dimensions of the device (figure 2) allowed an optimal use of the little space available inside the hand-held sensor housing.

During research for suitable low-cost Bluetooth modules, the scenario of using directly a Bluetooth transceiver chip rather than a Bluetooth module was also considered. The price of a separate Bluetooth chip (transceiver) can be as low as 25$ (LMX9020) but having a major disadvantage: these chips do not have the Bluetooth qualification, which allows them to be operated and produced as a Bluetooth-compatible device. Because the Bluetooth qualification of a product is a long and very expensive process, further development was done using the Amber Wireless module. This module is presented in figure 2. For the physical design the same module was used but with an external antenna connector instead of the integrated ceramic antenna that can be seen on the top of the module.

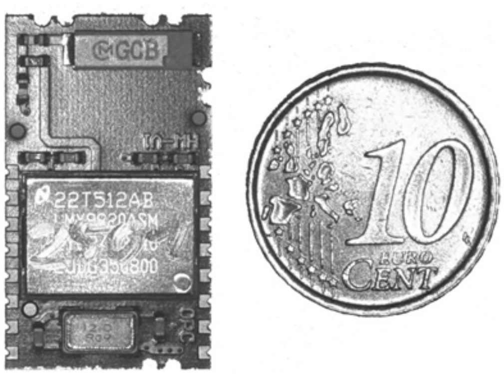

Figure 1. The Amber Wireless Bluetooth module with integrated ceramic antenna (top)

III. DESIGN CONSIDERATIONS

The design of the industrial wireless sensor has been divided in four functional blocks: the signal conditioning and A/D converter block, the logic unit, the memory and finally the power management block. These blocks had to ensure the high-speed, high-resolution acquisition of the sensor's output and further serial transmission of the sampled data directly to the Bluetooth module optionally via a memory buffer.

Adequate voltages for all functional blocks had to be supplied by the power management block. The power management considerations will be detailed in the next paragraph.

The logic unit had to be in line with several constraints: the sampling frequency of the entire system should not be less than 50 kHz with a resolution equal or higher than 12 bits/sample; another restriction was that of the serial communication needed by the Bluetooth module; a very restrictive issue was the lack of space, hence the need to find a versatile all-in-one solution.

After considering more microcontroller families such as AVR (Atmel) and PIC (Microchip), the final choice was the Analog Devices ADuC812 microcontroller, a fully integrated 12-bit data acquisition system-on-a-chip. It features a maximum sampling rate of 200 ksps, 8-channel precision self-calibrating A/D converter, on-chip voltage reference, dual-DAC, 3 timers and 9 interrupt sources. The microcontroller is based on an 8-bit 8052 core operating at a maximum clock frequency of 16 MHz. There are 8 Kbytes of Flash program memory and 640 bytes of Flash data memory and 16 MBytes external addressable memory space, which can be written at high speed through an integrated DMA controller. This latter characteristic, quite rare for a microcontroller, allowed the system to sample the analog input at the highest possible rate (160 ksps), writing the 12-bit samples into the external SRAM memory. Other advantages of this microcontroller are the integrated UART and SPI serial interfaces with variable baud rates, small footprint (56 pin PQFP package) and a reasonable price (15$).

Having an integrated A/D converter with internal voltage reference simplified the design of the signal-conditioning block, which was reduced only to a dual operational amplifier performing level adaptation and shifting to convert the differential output voltage of the sensor (± 10 V) to the 0 – 2.5 V analog input of the microcontroller. The DAC output of the microcontroller was used as a variable voltage reference for driving a Burr-Brown instrumentation amplifier in a programmable offset configuration.

An external low-power 512 KBytes 70 ns SRAM memory chip was used to store the data sampled from the sensor's output. The memory was connected to the microcontroller with two 8-bit latches.

The Bluetooth module was connected to the microcontroller using only three wires of the serial interface, RX, TX and GND. Hence, software handshaking is performed using start and stop bits.

The wireless sensor was designed to operate in one of two different modes: continuous sample and single-shot. In the continuous sample mode the voltage generated by the transducer is sampled by the A/D converter and formatted by the microcontroller in order to be sent to the Bluetooth module over the serial interface. The maximum sample rate in this operating mode is limited by the baud rate with which the Bluetooth module can send the data. The standard baud rate at which the sensor has been operated was 115.2 kbps. First successful tests have been done also at a baud rate of 460.8 kbps.

The single-shot mode can use the maximum sampling frequency of the A/D converter because the data is first written into the SRAM memory using the integrated DMA controller of the ADuC812. Data is then read sequentially from the memory and transmitted serially to the Bluetooth module.

A PDA played the role of the other peer, receiving and displaying the serial data on the screen. The transfer and visualisation software for the PDA was written in c sharp within the Microsoft .NET environment.

IV. Power management

As mentioned in the introduction, power consumption was a crucial issue when designing the system. Besides the need to assure a long battery life by minimizing consumption special voltage requirements of the strain-gauge transducer imposed further limitations.

The strain-gauge transducer needs a voltage supply of ± 12 V at some 150 mA that had to be generated from a 3.7V LiIon battery. The DC-DC converters existing on the markets can generate the ± 12 V only from voltages superior to 5 V so there was the need for a intermediary DC-DC converter. The first prototype of the wireless sensor used a MAX756 step-up converter from Maxim. Although versatile, this converter proved to function not so well at the limit of its 200 mA capacity, which in this design is quite often reached. Therefore, another DC-DC converter was found, the LT1302 from Linear Technologies. This step-up converter has the highest switch current rating of any other similarly packaged (SO-8) switching regulators present on the market, being able to reach 600 mA at 5 V, more than enough for the current design.

For the second DC-DC converter, due to constraints in terms of space, there was only one option, the NMA0512 from C&D Technologies.

The microprocessor, memory and Bluetooth module were all fed with a voltage of 3.3 V obtained from a MIC2920 voltage regulator from Micrel connected to the output of the first DC-DC converter (5 V).

The first prototype of the wireless sensor was built in separate modules in order to measure the current needed by each functional block. Table 1 presents the measured peak values for each block.

All these values refer to the case when each block is active, in order to calculate the maximum power consumption. The Bluetooth module could be configured to reduce its power consumption when idle to around 10 mA, the 50 mA being reached only when transmitting/receiving data or making inquiries. The microcontroller has also power-saving features: when not used, it can be powered down into a sleep mode, lowering the consumption of the logic unit together with the SRAM memory to less than 5 mA. The biggest consumer of all is the power management block together with the strain-gauge transducer. By using the microcontroller and a small additional circuit, the 120 mA of the power management block were reduced to around 20 mA in the idle state. Therefore, in idle mode, the power consumption of the entire wireless sensor was around 25 mA, meaning an autonomy of more than 24 hours with a 700 mAh LiIon Varta battery.

TABLE I.
CURRENT CONSUMPTION FOR THE FUNCTIONAL BLOCKS

Block	Peak current [mA]
Signal conditioning	10
Logic unit + memory	70
Power management + transducer	120
Bluetooth module	50
TOTAL	**250**

V. Physical Design

The first prototype, although carefully designed, revealed many flaws in terms of PCB layout, selection of parts and electromagnetic interferences. The two DC-DC converters used in the power management block are switching devices that inherently induced electromagnetic noise in the analog circuitry, disturbing the signals received from the transducer.

For the second prototype, to counter these unwanted effects, high-quality inductors have been used, with a low DCR (under 0,05 Ω) and able to handle currents up to 3 A without runaway saturation. Capacitors with low ESR allowed a stable operation with little or no ripple.

A 4-layered, 2-sided PCB layout was designed with carefully routed ground planes and strictly separated digital and analog ground. The capacitors and inductors of the power converter circuits were placed as close as possible to the DC-DC converters to avoid antenna effects. Decoupling capacitors have been consequently used. Furthermore, thin metallic shields have been used to separate the switching devices from the rest of the circuit.

Programming the microcontroller and Bluetooth module was accomplished by routing a connector to the serial communication lines and interchanging RX and TX wires for selecting one device or the other.

Except the 5 V to ±12 V converter, all components were surface-mounted devices, allowing to maintain a small PCB layout in order to fit into the original sensor housing. The dimensions and one side of the layout can be seen in Figure 2.

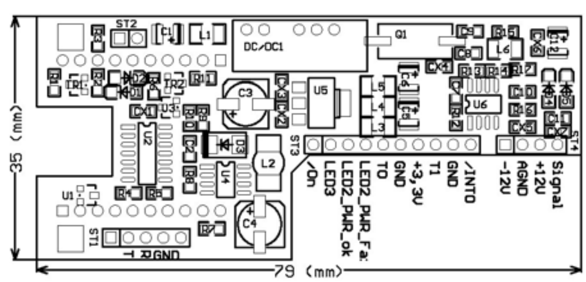

Figure 2. PCB Layout of the wireless sensor

The rectangular hole in the left part of the design accommodated the antenna connector of the Bluetooth module, which was soldered using pin headers on the top of the PCB board. The cut-out in the lower part of the layout was due to the original sensor design which featured in that position a trigger button and a LED to signal operation state.

The PCB was glued to the bottom cap of the sensor case and reinforced by the external antenna connector, which was fed out through a hole in the cap. The physical design was completed with an ON-OFF switch and a charging plug, both with IP-65 protection class and both mounted on the bottom cap. Details can be seen in figure

3. The battery, not pictured, is mounted on the top of the PCB, in the right part of the picture. The bottom of the Bluetooth module can be seen in the left part of the picture.

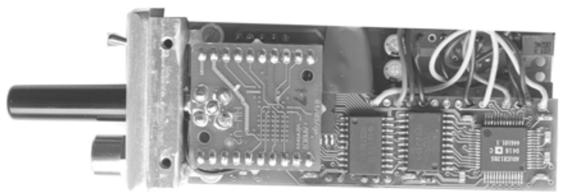

Figure 3. Layout of the wireless sensor

VI. TESTING

The sensor was thoroughly tested in various industrial environments. The Bluetooth transmission was not considerably influenced by electromagnetic interferences, the range being around 20 meters due to the high gain of the external stub antenna and due to the retransmission and error checking mechanisms implemented within the microcontroller and the PDA software. The only effect of interferences was the retransmission of some of the data packets, which led to longer waiting times when downloading the data from the sensor to the PDA.

The sensor's precision was tested using a high precision function generator, which allowed calibrating the analogue part and observing the influence of the switching DC-DC converters on the sampled signal. The spikes induced by these converters over the analog signal could not be completely eliminated despite shielding measures, but the amplitude of the electromagnetic noise was considerably reduced, at levels comparable with the A/D precision. Considering the integral nonlinearity of the ADC converter (max. ± 1.5 LSB at 12 bits and V_{ref} = 2.5 V), the precision of the entire measuring system was more than sufficient for the specific application field of this type of sensor (strain-gauge).

VII. CONCLUSIONS, COMPARISONS AND FUTURE WORK

The initial goal to design a small-sized, low-cost industrial wireless sensor based on the Bluetooth wireless communication standard was achieved.

The size of the designed circuit, including the wireless module and the power source was kept small in the limits of 80 x 35 x 25 (mm) (L x W x H), fitting perfectly into the original sensor housing. The precision of the measurements, as well as the sampling frequency is satisfying for the usage field of this type of transducer. The cost of the entire design did not exceed 300$ which was within the proposed price limit.

The improved manageability of the wireless sensor paired with a PDA was tested extensively and delivered encouraging results also in terms of system stability.

Low-power Bluetooth industrial sensor modules can be found on the market in various configurations and prices. The present work, being a dedicated design for a specific sensor, is hard to compare with other Bluetooth sensors having standard sensor inputs. Similar dedicated embedded commercial designs were, in most of the cases, biomedical applications such as blood pressure or temperature meters. Nevertheless, none of the systems on the market had the possibility to acquire signals at a rate higher than 5 KHz. The single-shot mode of this design, with a sampling frequency up to 200 kHz, could not be found in other existing products.

Future work will focus on refining the existing design by testing other microcontrollers with higher sampling rates and also testing the behaviour of the system at higher transfer speeds. Improving the precision of the sampled data and raising the immunity to the interferences generated by the DC-DC converters will be considered too.

The existing logic platform will be used to develop also alternative wireless sensor designs with WLAN and ZigBee modules if the implementations of these standards will move towards lower power consumption and better availability.

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