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Smart Silicon Sensors

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***Abstract** - In this paper, we discuss some of the trends in the industrial designs of smart sensor systems. High performance sensor systems have been implemented by combining the sensi.ng and signal processing functions on the same chip. Some applications of magnetic field measurements will be discussed.*

***Keywords** - Smart sensors, Hall sensors, magnetic field, Earth-magnetic field.*

I. INTRODUCTION

This paper discusses some state-of-the-art examples of high-performance industrial sensor systems. The low transistor cost in combination with the continuous generation of new ideas has led to a steady growth of intelligence on a single IC. Complete sensor systems have been **completed** on **one** chip **wherever ancient** functions, such as signal conditioning, AID conversion, data communication and the generation of reference and compensating signals are no longer performed by separate components, **however are** all integrated on **a similar** IC. This reduces overall system costs while improving the sensor performance at the same time. Costs can even be hrther reduced if the IC technology allows for integration of the sensor device in the same substrate. Almost certainly, the best example is the smart temperature sensor [1],[2],[3], where the temperature sensing device is formed by a pair of bipolar transistors. Inaccuracies can be as small as *2"C over the temperature range of -50°C to +15O"C. Singlechip smart temperature sensors are now available for less than $1 in which the temperature sensor, the interfacing electronics, the A/D conversion, calibration circuits and bus interface **are** all ingeniously embedded **within the style**.

Similar technologies are already available or emerging of which, among others, acceleration, capacitive, flow and magnetic-field sensors have very high potential. Figure 1 shows the general hardware configuration of such a smart sensor system [4], [5]. Although it is possible to combine **a wise detector** with a microcontroller on the chip, it is rarely done because of unnecessary system complexity, high current consumption, interference, incompatible IC process requirements, etc. Furthermore, there is an enormous variety of low-cost microcontrollers available. Therefore, for smart sensors it is sufficient to embed the simplest form of control, processing and memory while being able to communicate with any microcontroller.

The rest of this paper describes three project examples where the system aspects as previously described will be addressed wherever appropriate. We will do that for **two** applications of magnetic-field measurements. Finally, we will describe a general-purpose instrumentation IC which was developed for applications in outer space.

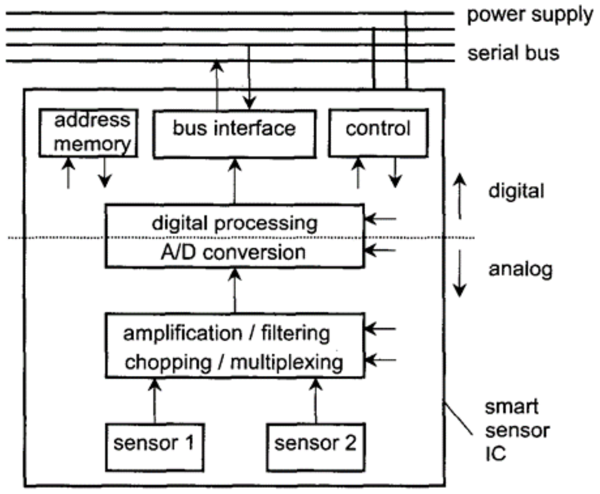

Figure 1. Basic functions in a smart sensor IC.

II. MAGNETIC FIELD SENSORS

Despite the capabilities of (digital) signal processing, smart sensor accuracy primarily depends on the accuracy of the sensing element. Therefore, a main part of the design effort goes into the selection of the physical effect and into the design of the sensor structure. This will be illustrated for magnetic field sensors. Magnetic fields can be measured with various types of sensors using, among others, the Hall effect [6], [7], a magnetoresistive effect and the fluxgate effect. The demand for low-cost high-performance solutions force the designs towards using the Hall-effect, because it is the only effect that can be implemented in a standard CMOS technology.

Hall sensors

The simplest Hall element uses a square plate of N-well in a p-type epitaxial layer. Each corner of the plate has one contact. When a voltage *V*, is supplied across one pair of contacts, then a magnetic field *B* perpendicular to the Hall plate generates a voltage *V*, across the sensing pair of contacts according

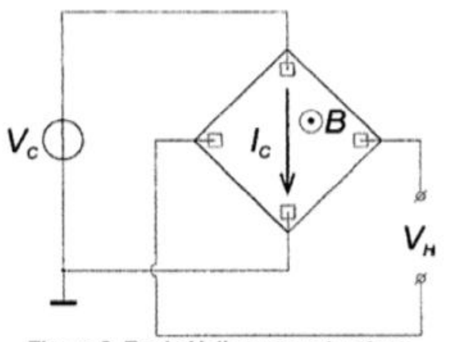

Figure 2. Basic Hall-sensor structure.

Typical sensitivities of Hall plates fabricated in standard CMOS technology are in the order of 100mVNT. Most applications require magnetic field strengths to be measured in the signal range of 40yT (earth-magnetic field) up to 250mT (strong magnet). It is the lower end of this **vary** that **build the employment** of CMOS Hall sensors **terribly** difficult. The main problem for realizing a low-cost compass **exploitation semiconductor.** Hall sensors are its offset and, even more important, the drift of the sensor offset. Commercially available Hall sensors typically operate over ranges that start at 1mT and have noise levels in the order of 50-100pT.

Hall-sensor offset and drift The perfect Hall sensor does not develop an output voltage when a magnetic field is absent. In practice, all Hall sensors have offset as a result of material in homogeneities and because of the mechanical construction of the sensor. This offset can be compensated for by means of calibration as long as the offset is constant. Unfortunately, this is not the case. Mechanical stresses, temperature variations and aging cause the sensor offset to fluctuate. This requires frequent re-calibration of the sensors, which is unwanted.

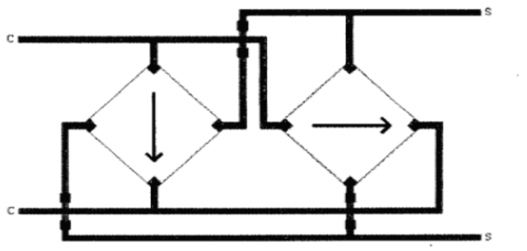

Figure 3. Offset compensation by parallel connection of two Hall plates, which are 90° rotated.

Furthermore, realistic signal levels of a few yV become completely masked by offset levels that can be tens of mV. This demands for front-end electronics with an extremely wide dynamic range. At Delft University, research has been carried out for more than ten years to solve these problems.

This has **semiconductor diode** to the **alleged** spinning-current Hall plate [8].

As shown in Figure 3, the first step towards the spinning current Hall plate is a parallel connection of 2 Hall plates that are rotated by 90". Offset caused by mechanical stresses will then be compensated for. The compensation gives approximately ten times improvement over the uncompensated Hall plate and is limited by mismatching effect of the two Hall plates. Figure 3. Offset compensation by parallel connection of two Hall plates, which are 90" rotated. The spinning-current Hall plate as shown in Figure 4 combines the two-plate offset-compensated structure into a single circular Hall plate with multiple contacts. The structure shown uses 12 current directions where the rotation of the current low takes place in the time domain. The current direction will be spun around the central axis step-by-step. Meanwhile the Hall voltage is measured at the contacts that are perpendicular to the current flow. Offset compensation now takes place in time by summation of the measurement results. This method is capable of reducing the offset down to 10pT [9].

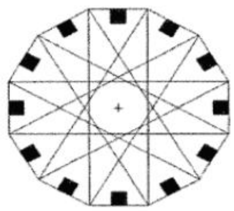

Figure 4. Spinning-current Hall plate.

ELECTRONIC COMPASS

The spinning-current Hall-plate forms the basis of the Xcnsor EMF-01 chip (Figure 5).

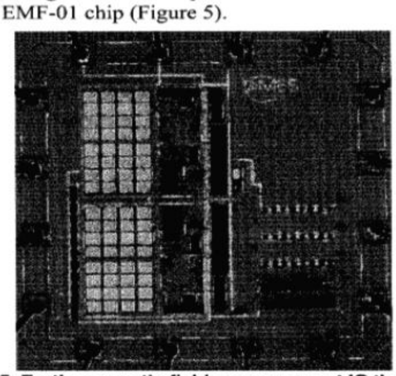

Figure 5. Earth-magnetic field measurement IC that uses a spinning-current Hall plate.

This chip uses a :spinning-current Hall plate with 8 contacts. By using three chips in an orthogonal set-up, it is possible to measure the magnetic field vector in a reference plane. Two chips are sufficient for usage as an electronic compass. The signal frequency band is limited to a few Hz only.

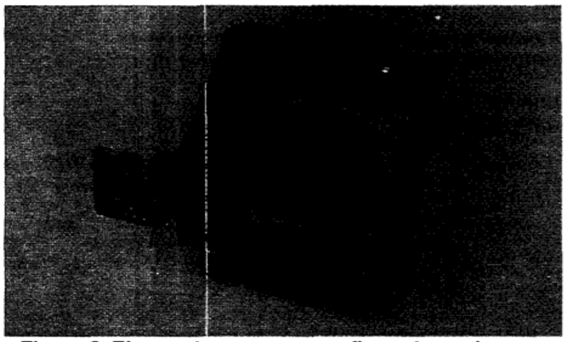

Figure 6. Electronic compass configuration using two orthogonally packaged EMF-01 ASICs.

This IC is a first development towards a smart compass [lo]. It contains some basic signal processing to amplify the low-level **device** signal to **tier wherever** it **are often** handled by an A/D converter. The ASIC contains a switching .array, their control logic and a differential amplifier with pre-set gain of 100 (Figure 7).

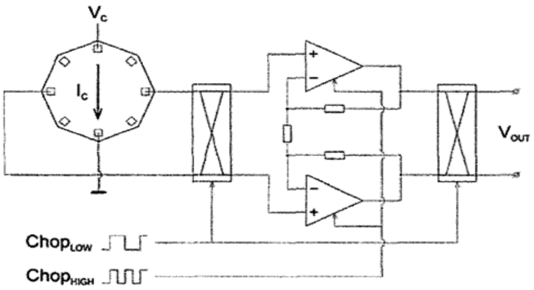

Figure 7. Schematic overview of the EMF measurement IC.

Chopping techniques have been used to separate the sensor signal from undesired sources of offset and l/f noise. This chop frequency must be chosen well above the l/f-noise frequency of the font-end amplifier (approximately 20kHz) for minimum noise contribution. Unfortunately, the current direction in the Hall sensor is allowed to change at 10Hz maximum for otherwise thermal settling effects will modulate the Hall-effect. Therefore, a double chopping scheme was applied to the sensor read-out electronics. The high-frequency chopper, which runs at 2kHz, removes the differential amplifier's offset and l/f-noise. The residual offset of the differential amplifier will be removed by the second, low-frequency chopper. This chopper runs at 16Hz only and modulates the sensor signal to a 16Hz band. The current direction in the Hall sensor is changed every 125ms (8Hz), so one measurement cycle takes 1 second to complete.

Hydraulic cylinder height application

In an absolute position measurement system for hydraulic cylinders [ll] a wide dynamic range of magnetic field strengths has to be handled. This application uses a large (up to 50 meters) metal cylinder with a machined coding system. This coding system consists of local grooves arranged in a unique pattem.

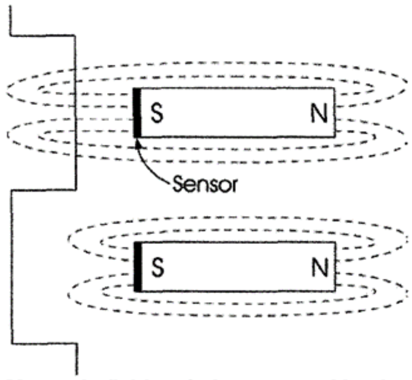

Figure 8. Magnetic-field variations caused by the presence of metal.

This code, with built-in redundancy and error-checking, allows for interpolation of the precise position down to 50pm with respect to the groove edges. The local code, i.e., the groove pattem, is read-out by an array of magnetic sensors.

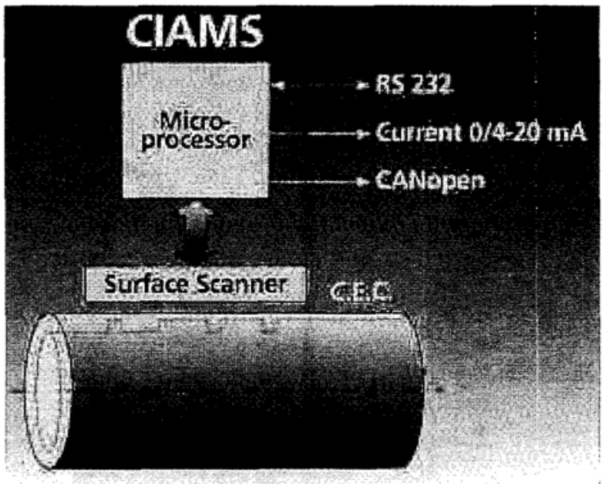

Figure 9. Block schematics of the position measurement system.

A permanent magnet of approximately lOOmT creates a magnetic field that will be somewhat disturbed by the height of the grooves. The array of magnetic sensors measures these disturbances. The signal levels to bemeasured are in the order of O.lmT to 1mT. Obviously, the signal levels can be 3 orders of magnitude below the offset value. Since the position of the measurement unit can be fixed for long periods of time, the signal frequency band is near DC. Hence, the low-frequency noise spectrum, e.g., offset, coincides with the signal spectrum. Therefore, the interface electronics must be able to handle the full dynamic range. Meanwhile, the drift of the sensors must be well below the signal levels measured. These problems can only be overcome by using spinning-current Hall sensors.

III. INSTRUMENTATION ASIC FOR SPACE

APPLICATIONS For the PROBA satellite mission, which was launched in October 2001, a low-power radiation-tolerant data- acquisition module was designed [12]. This module consists of a custom designed ASIC and a RadFET. The RadFET is used as a dosimeter to determine how much radiation has penetrated into the satellite. The ASIC contains a temperature sensor and has programmable sensor interface circuits for the read-out of a broad range of external sensors, like thermistors, potentiometers and thermocouples. Furthermore, the ASIC is equipped with a 14 bits C A/D converter. Auto-calibration can be performed to improve the system's accuracy. The module is programmed and activated using an IS2 serial bus interface. Each module has a unique bus address which is internally set in a 5-bit register. Hence, up to 32 modules can be connected to the bus system, which can be controlled by an external microprocessor. The device consumes 20mW (5V supply) and is packaged in a cube of 0.6cm3 with 8 wires. It is fabricated in bipolar technology because of its radiation tolerance (>100kRAD).

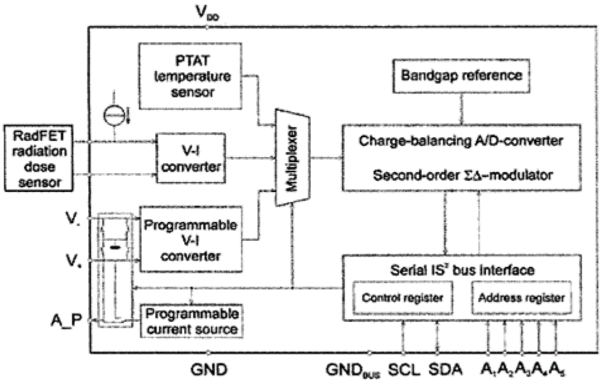

Figure 10. Block schematic overview of the space-qualified instrumentation ASIC

As shown in Figure 10, the data acquisition part of the chip contains a multiplexer, followed by a programmable-gain amplifier with offset compensation. Digitilization is carried out by a 14-bit second-order CA converter. The chip has a two-wire serial bus interface running at 1 OOkHz.

Internal Sensors

The data-acquisition module contains two sensors: a radiation dose sensor, consisting of an off-chip RadFET dose monitor and an on-chip band gap temperature sensor.

The RadFET dose sensor is based on the degradation of a MOSFET, causing a well determined increase of threshold voltage with radiation dose. This degradation also takes place when the ASIC is powered down, which makes the ASIC very suitable for low-power radiation monitoring.

The RadFET is biased at a current of 40pA while the voltage of the RadFET is read-out by the ASIC. The radiation dose sensor data can be selected by use of the control register.

Each ASIC is equipped with an internal temperature sensor, based on a PTAT current source. The range of the temperature sensor is -30 to 100°C. The sensor has an uncalibrated accuracy of +5"C and improves to within *1"C after calibration.

Programmable analog front-end description

The programmable analog front end of the ASIC consists of a general voltage interface, a bias current source, auto- zero switches and a sensor multiplexer. The analog front- end is suitable to read-out of a broad range of exothermal sensors, like thermistors, potentiometers and thermocouples.

The ASIC contains a programmable voltage interface with values of 42mV, 620mV or 2.6V. The desired range can be chosen by the control register. The ASIC contains a programmable bias current source. The value of the current can be programmed to be lpA, 16pA or 256pA. Furthermore, the current source can be disabled. This high-ohmic state can be used to do an auto- zero measurement. Because the absolute values as well as the temperature behavior of the current are not accurately known on beforehand, the current source is intended for biasing resistors in ratio-metric configuration (bridges, potentiometers, Hall plates) rather than as a reference current source. The current source is connected by a programmable switch to either the V+ or the A-P terminal. By changing the current from one terminal to the other ratiometric measurements can be performed.

Each ASIC is equipped with 2 pairs of auto-zero switches, which offer a connection of the analog inputs to GND in various ways. One pair switches V- and V+ simultaneously to GND. The other pair switches V- and AP simultaneously to GND. The switches have a high impedance and low-drive current capacity. They are inherently shortage protected. They are controlled by the control register and can be used for several purposes. Firstly, for a (soft) common-mode reference to ground for floating voltage sources such as thermocouples. Secondly, for the auto-zero of floating voltage sources.

The ASIC contains a programmable sensor multiplexer, which connects the AID converter to either the RadFET sensor, to the temperature sensor or to the general purpose interface.

Analog-to-Digital Conversion

The analog-to-digital conversion has been split into two parts. First, an on-chip second-order 14 bits XA modulator converts the sensor information into a bitstream. This bitstream will be filtered off-chip after transferring it over the serial bus

As the 1-bit serial output of the sigma-delta converter is a very convenient sensor output signal, this digital filter is not incorporated in the ASIC. Instead, it should be implemented in software on the system's computer or microcontroller. Or, it can be implemented in digital hardware on a separate chip which is, for example, connected to the sensor bus. The XA converter uses the bus clock frequency (120kHz) as a time reference during the conversion.

The ASIC is capable to communicate with a master microcontroller by means of a simplified 12C protocol called IS2 [13]. This simple bus structure requires three wires only: a common ground line, a serial clock line (SCL) and a serial data line (SDA).

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