SMART SENSOR INTERFACES: AN INTRODUCTION

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Abstract

This paper is an introduction to smart sensor interfaces. Definitions are given and some market numbers are shown. Most smart sensors require low-offset, low-noise amplifiers. Dynamic offset-cancellation techniques are the solution for that and principles of autozeroing and chopping are shown. Examples of a smart temperature sensor, flow sensor and magnetic sensor are shown.

1. Introduction

The purpose of this paper is to give an introduction to smart sensor interfaces. As the title is already announcing, it will not be possible to do in-depth analysis, but an overview will be given of the options and implementations that are currently possible and available. Readers are encouraged to use references to probe further.

1.1 What is a smart sensor?

Although the definition of a smart sensor may look trivial, it has not been that trivial in the past. Some people have called their silicon micro-machined acceleration sensor with integrated piezo-resistors a smart sensor, while others have made a general-purpose smart sensor interface. In both cases the word "smart" has been misused.

In this paper we will use the following generally accepted definition of a smart or intelligent sensor:

J. H. Huijsing et al. (eds.), Analog Circuit Design, 3-22.

A device that incorporates both a sensing element and dedicated interface electronics.

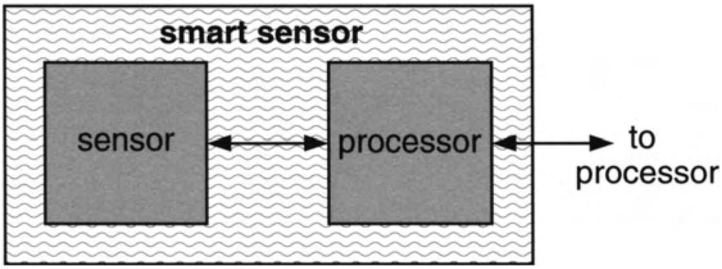

Fig. 1. Smart sensor

A graphical representation is shown in figure 1. This does not necessarily mean that the sensor has to be made with IC technology or that the interface electronics need to be integrated on the same substrate, although that will be the case in most implementations. The key factor is that both the sensor and the electronic readout circuitry are *matched* and sold together.

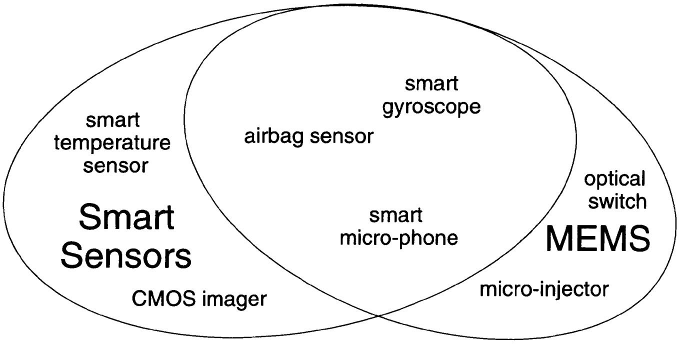

Fig. 2. Comparison of Smart Sensors and MEMS

1.2 Are MEMS and smart sensors the same?

A term that is popping up often with smart sensors is MEMS. MEMS stands for Micro Electro-Mechanical System. MEMS and smart sensors have a big overlap, but are not the same. Please have a look at figure 2.
Most MEMS are smart sensors like airbag sensors, gyroscopes and integrated microphones. However, a smart temperature sensor is not a MEMS, because it is not micro-machined. Micro-actuators like an optical switch (see figure 3, [1]) or a micro-injector are MEMS, but are no sensors. And finally pressure and acceleration sensors without electronics are genuine MEMS, but not smart sensors.

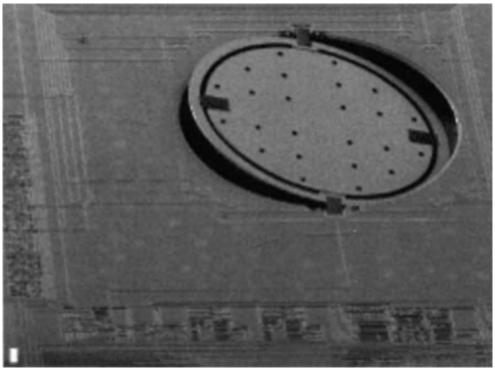

Fig. 3. Smart optical switch (courtesy of Analog Devices)

1.3 Why make sensors smart?

Key words in smart sensor commercials are size, price, performance and reliability. Of these four reasons to make sensors smart, at least one is always true: Smart sensors require less space than conventional sensors. However, price and performance are usually exchangeable. For example, a thermistor is cheaper than an integrated temperature sensor, but the latter one has better performance, perhaps not in accuracy or sensitivity, but certainly in linearity and output interface. Improved reliability is certainly true for some micro-mechanical sensors or sensors that have gone to a different signal domain, like thermal wind sensors. However, one can not say in general that smart sensors are more reliable. Still, smart sensors can have several advantages over normal sensors, but it varies per application.

1.4 Markets for smart sensors

Some may ask: Are there any “killer” applications for smart sensors, or is it still a niche market, propelled by academics? This question can be easily answered by a firm: Yes, there are killer applications and you are using them everyday. Probably the most appealing smart sensor is the airbag sensor as used in over 90% of all new cars sold worldwide, see figure 4 [2].

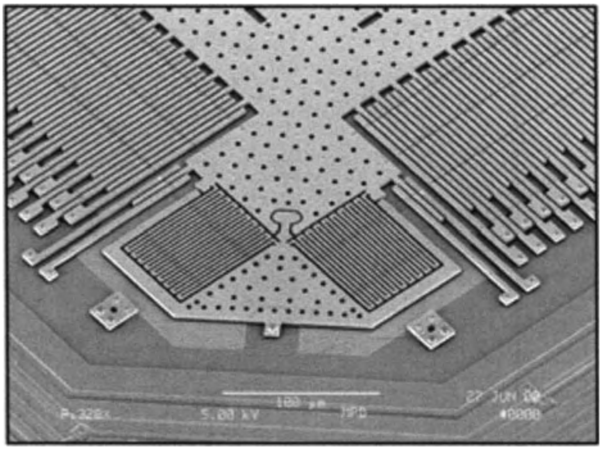

Fig. 4. Smart capacitive acceleration sensor (Courtesy Analog Devices)

The typical airbag sensor is a micro-machined capacitive acceleration sensor with readout amplifier on the same substrate. A good other example is the smart temperature sensor with integrated Sigma-Delta ADC and bus interface as used in all desktop and notebook PCs for thermal management. Both have accumulative sales over 200 million devices in 2002. And we won’t talk here about magnetic sensors, CMOS imagers, smart microphones, fingerprint sensors and gyroscopes which represent significant markets as well.
However, the interesting fact is that all above mentioned smart sensors have developed in the last decade! They were not there ten years ago or were hardly sold! It can therefore easily be stated that the penetration speed of smart sensors is greater than micro electronics was 30 years ago.

2. Properties of smart sensors

What is so special about smart sensors that we can't use our standard electronics for it? To answer this question we will need to understand more about the special properties of smart sensors and what the consequences are for the interface electronics.

2.1 Signal domains

A commonly used definition of a sensor is:

> *A device that transfers information from one signal domain into another.*

That *other* domain is usually the electrical domain, but that is not necessary (for example a liquid thermometer). However, a *smart* sensor always transfers information into the electrical domain.

Some readers would remark that actuators (for example a loud speaker) also fit the above-mentioned definition of a sensor. That is definitely true and the collection of sensors and actuators is called *transducers*. However, one should keep in mind that a sensor is a transducer, but a transducer is *not* necessarily a sensor.

Another question that might pop up is whether a current sensor is a sensor, because it does not transfer information from a signal domain into a *different* domain. The answer to this question is dependent on the implementation. If the current sensor is implemented by a Hall sensor sensing the magnetic field around a close-by conductor, then this sensor is definitely a sensor according to the definition mentioned above. However, if the current sensor is implemented by a resistor, then it does not fit the official definition.

Until now, scientists have defined six signal domains: Electrical, Mechanical, Chemical, Magnetic, Thermal and Optical. The last domain is also referred to as Electro-Magnetic or Radial. It seems that these are all the domains, but it may be that we will find more domains in the future.

Figure 2 is a graphical representation of some existing *smart* sensors and how they fit in the above described domain model.

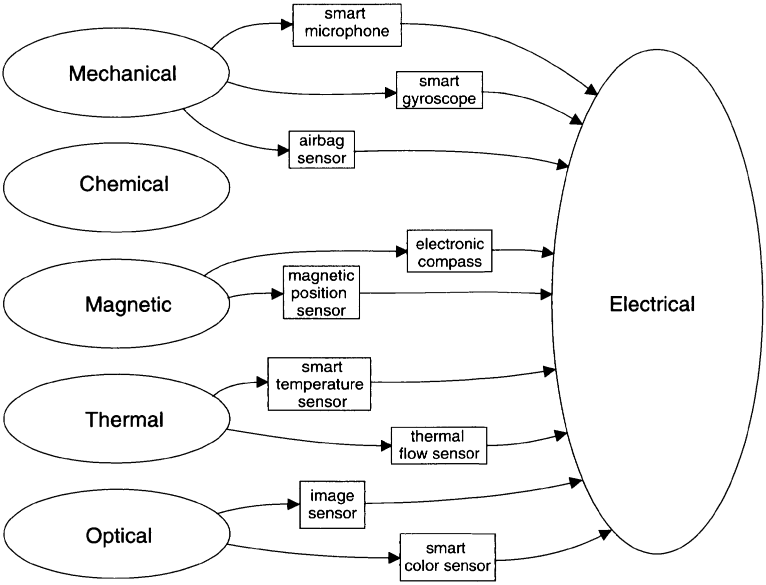

Fig. 5. Smart sensor overview in signal domain model

One of the difficulties with this simple model is the position of "hybrid" (or two-domain) sensors like the magnetic position sensor and the thermal flow sensor. For example, the position sensor could also be well placed in the mechanical domain, because position is primarily mechanical information. However, since we are focusing on the *smart* part of the sensor, the magnetic position sensor is placed in the magnetic domain, because the input domain of the *smart* sensor is magnetic.

2.2 Compatibility with IC technology

Zooming in on figure 5, it can be remarked that there are no killer applications for smart chemical sensors. This does not necessarily mean that there are no smart chemical sensors at all, but they are more difficult to make. This has to do with the fact that chemical sensors are hardly compatible with IC technology. Most smart sensors utilize specific properties of silicon to measure their input signal. For example, temperature sensors use the base-emitter voltage dependence of bipolar transistors, magnetic sensors use the Hall-effect, gyroscopes (see figure 6 [3]) use the mechanical properties of poly-silicon and CMOS image sensors use the optical properties of silicon. However, some smart sensors add additional materials to the existing silicon IC-technology, usually in post-processing steps. An example of this is a smart magnetic sensor based on the Magneto-Resistance effect.

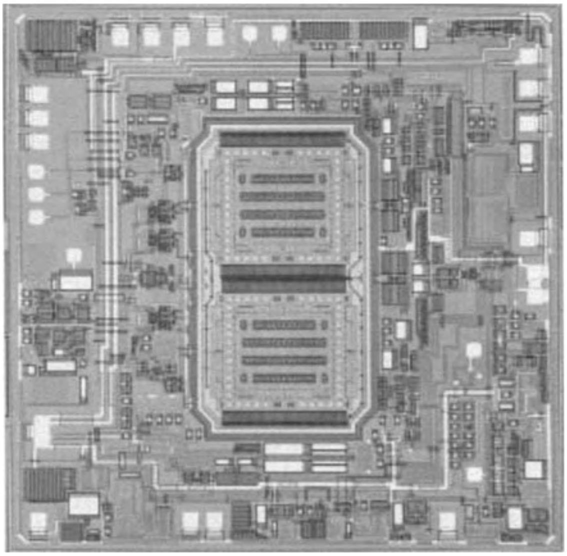

Fig. 6. Smart gyroscope (Courtesy of Analog Devices)

2.3 Electrical properties of smart sensors

The previous paragraph showed that most smart sensors are based on specific properties of silicon. However, the output domain is always electrical, which implies that the output signal is a voltage, a current or a "modulator". A modulator can be an impedance, a capacitance or an inductance and theoretically any other combination of these elements. For example, thermocouples have a voltage output, optical sensors usually have a current output, while mechanical sensors tend to have capacitive or resistive outputs. Hall sensors generate a voltage output based on a current input and are therefore modulators.

2.4 Sensor signal references

Although smart sensors can have different kinds of output signals, not all output signals are equally useful for processing. Because nowadays processing is mainly done by digital processors, the preferred output of a smart sensor is a digital format.[1] Because a digital format has no unit, a *reference* is always needed.

If a sensor has a voltage output, this is usually a bandgap voltage reference. One of the most important features of a voltage reference is that it is stable under all circumstances. However, for "modulating" sensors, one tries usually to make a reference that is insensitive to the sensing signal, but *tracks* other undesired signals. A good example of this is the reference capacitor seen in airbag acceleration sensors or the reference resistor seen in piezo-resistive pressure sensors.

For voltage output sensors, the reference is usually introduced just before the Analog-to-Digital Converter (ADC), see figure 7.

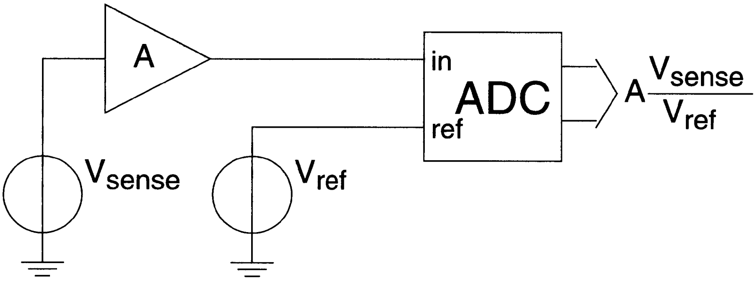

Fig. 7. Voltage output with bandgap voltage reference

For modulating sensors, the reference is usually introduced much earlier. A good example of this is the "Wheatstone" bridge as shown in figure 8 or the charge amplifier as shown in figure 9. Be aware that modulating sensors don't need an additional voltage reference!

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[1] Although "digital" is officially not part of a signal domain because it has no unit, it is usually placed in the electrical domain, because most digital representations are in the electrical domain. However, the signal from a CD or hard disc is definitely digital, and definitely not electrical.

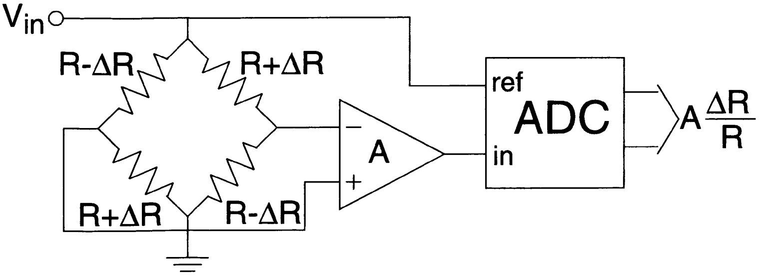

Fig. 8. Smart resistive interface with reference resistor (Wheatstone bridge)

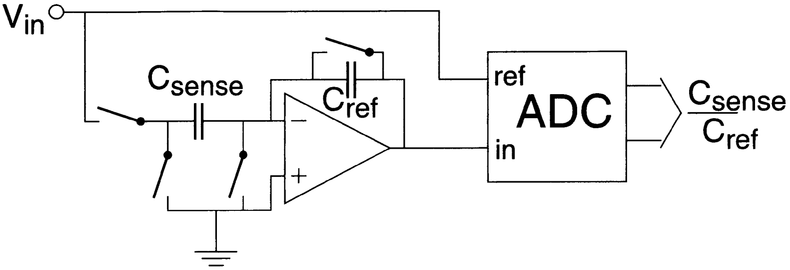

Fig. 9. Smart capacitive interface with reference capacitor

Smart sensors with a current output are a slightly different story. Ideally, one should make a current reference on chip, but it is much harder to make a good reference current than a good voltage reference, which is mainly due to the poor absolute accuracy and temperature stability of on-chip resistors. The solution to this is usually an external resistor.

3. Smart sensor interfaces

After this extensive introduction, we finally come to the point where this day is all about: Smart sensor interfaces. Why is the sensor interface such an important element? Because it is the component that, next to the sensor, will determine the overall performance of your smart sensor. And since it is usually impossible or expensive to improve the performance of your sensor, the smart sensor interface is the place where you should put your effort in.

3.1 Amplifiers

As could already be seen from the previous figures, the sensor signal is usually too small to be directly fed into an ADC. It first needs to be amplified to have enough amplitude to be compared with a reference.

What are the specifications of the amplifiers we are looking for?

Most sensors have pretty tiny output signals. Most common temperature sensors have output signals in the order of 200μV/°C[4], Hall sensors can have output signals less than 1μV. Bandwidths of the sensors are usually quite limited. Again temperature sensors have a bandwidth that usually not exceed 100Hz, pressure sensors are limited to approx. 1kHz, however, microphones can have a bandwidth up to 20kHz. Other specifications to look at are noise and the twin Common-Mode Rejection/Power Supply Rejection (CMRR/PSRR). Power consumption may be a problem in battery-operated smart sensors.

If we compare our wish list to "general purpose" amplifiers, we can conclude that most significant "mismatches" are found in offset and $1/f$ noise in CMOS amplifiers. The offset of a CMOS amplifier is usually in the order of typically 1mV. This offset is mainly determined by the area of your input transistors. To reduce the offset, one could decide to increase the size of the input transistors, however, the offset only reduces by the square root of the area, so you are running out of juice pretty fast. Almost the same is true for the $1/f$ noise. It can be reduced by spending silicon, but it only improves by the square root of the area. Actually, we can treat offset and $1/f$ noise as a single phenomena, although their physical background is definitely different, see figure 10.

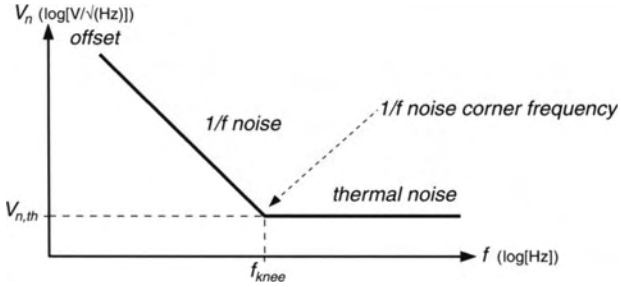

Fig. 10. Noise power spectrum of a CMOS amplifier

Why don't we trim the offset? Of course this can be done, but that doesn't reduce the $1/f$ noise and you still have the temperature drift, which can be 1-10 μV/°C.

Why not use bipolar instead of CMOS? Bipolar transistors have several advantages over CMOS like a 3-5 times lower offset and very little 1/*f* noise. However, there are a few reasons why bipolars are not commonly used for smart sensor interfaces. The most important one is the base current. Especially if you are trying to improve the noise performance by increasing the collector current, you are pretty fast hitting a point where the current noise and/or the current induced offset will become dominant. A good second reason is that the rest of your *smart* sensor, namely the ADC and probably some digital interfacing is made cheaper with CMOS.

3.2 Dynamic offset-cancellation techniques

A third good reason that I haven't mentioned yet is the great solution that exists for the CMOS amplifier offset and 1/*f* noise problem. They are generally called dynamic offset-cancellation techniques. They can be distinguished from "static" offset cancellation techniques like trimming, because they reduce offset "on the fly". Dynamic offset-cancellation techniques can reduce the offset to the micro-volt level, while also removing the 1/*f* noise.

3.3 Auto-zeroing versus chopping

There are basically two families of dynamic offset-cancellation techniques: Auto-zeroing and chopping[5]. Auto-zeroing is shown in figure 11 and can be explained as follows.

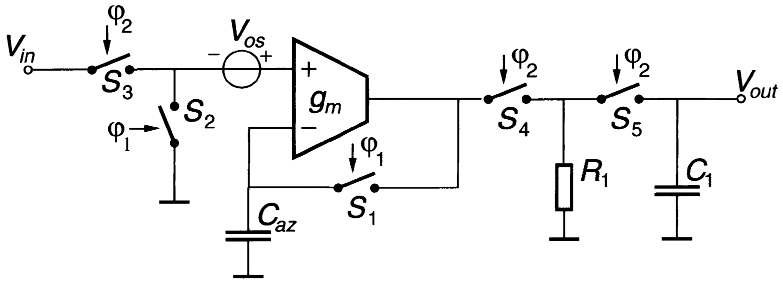

Fig. 11. Auto-zero technique

The offset-cancellation is done in two phases, a sampling phase φ_1, and an amplification phase φ_2. During φ_1, the input signal is disconnected and the input

of amplifier is connected to ground. The offset voltage is now sampled on C_{az}. During the amplification phase, this offset is subtracted, resulting in an output voltage that is free from offset. A sample-and-hold circuit is added to make the output signal continuously available.
The principle of the chopper technique is shown in figure 12.

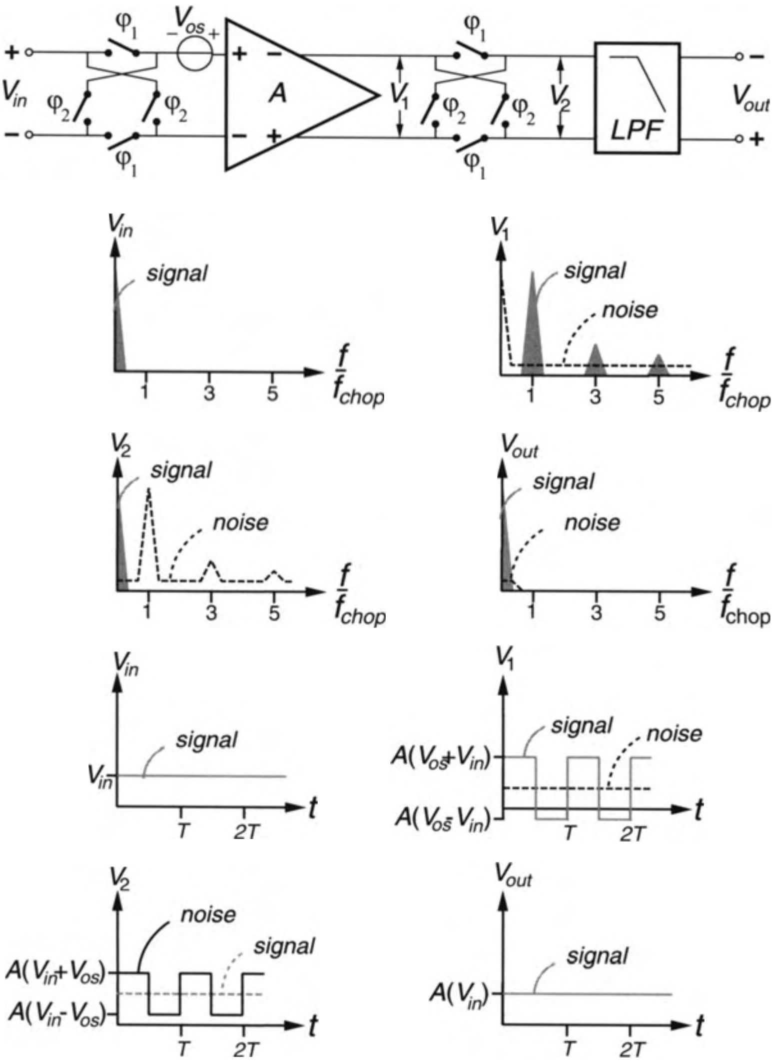

Fig. 12. Chopper amplifier principle

The input signal V_{in} is multiplied by a square wave signal with a frequency of f_{chop}. The modulated input signal is amplified and demodulated by the same signal. The offset is modulated only once and appears as modulated offset around the odd harmonics of f_{chop}. The offset and signal can then be separated by a filter. Figure 12 also shows a time-domain explanation of the same principle.

What are the pro's and con's of the above-mentioned techniques? The auto-zero technique has the advantage that it does not need a filter to remove the offset, which makes it better suitable to be used in opamps. The residual offset of both techniques is approximately the same. However, the biggest advantage of the chopper technique is the residual noise, which is shown in figure 13.

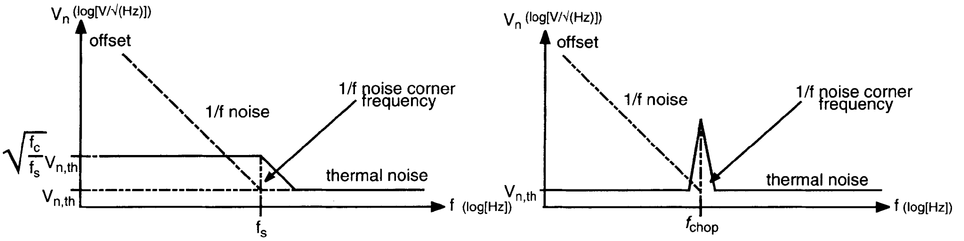

Fig. 13. Noise spectrum of autozero amplifier (left) and chopper amplifier (right)

The background for this difference is the fact that an auto-zeroed amplifier is a sampled system, while the chopper amplifier is a continuous-time system. The sampled auto-zero amplifier is folding back high-frequency noise to the base-band. In practical implementations, the noise of an auto-zeroed amplifier is two to three times higher than of a chopper amplifier.

3.4 Nested-chopper technique

The residual offset of both an auto-zero and chopper amplifier is in the order of tens of μV for a switching frequency in the order of 10kHz. This residual offset finds its origin in the charge injection of the switches. The residual offset is approximately linear dependent on the switching frequency for frequencies lower than the bandwidth of the amplifier. In most situations an offset of 10μV is sufficient and already lower than the noise. However, in very low bandwidth applications, it can be worthwhile to further reduce the offset. This can be done by making a combination of dynamic-offset cancellation techniques at different frequencies. A good example is the nested-chopper technique as shown in figure 14, which has a reported offset of less than 100nV in a bandwidth of 8 Hz. [6]

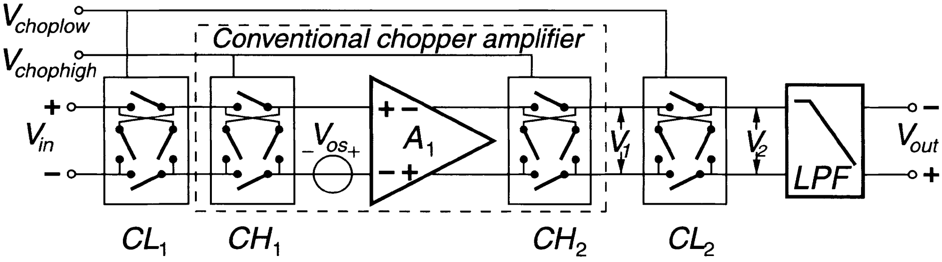

Fig. 14. Nested chopper amplifier

3.5 ADCs

The choice for an ADC topology that fits best for smart sensors, is not that difficult. Because the bandwidth is usually limited, a Sigma-Delta ADC is almost always suitable. Sigma-Delta ADCs have the advantage that they are low-cost and provide ample resolution, easily up to 16 bits. The Sigma-Delta sync decimation filter also fits well with the above-mentioned chopper techniques, because you can exactly place a notch of your sync filter on top of your modulated offset as shown in figure 15.

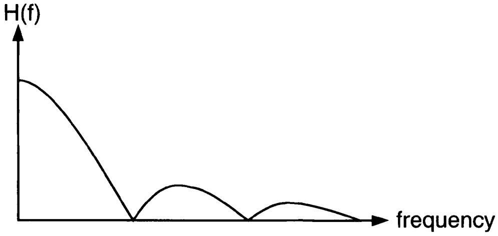

Fig. 15. Frequency response of sinc filter

The choice between a first-order or second-order Sigma-Delta ADC is mainly dependent on the required resolution and the speed. For integrated temperature sensors one can see a shift from first-order to second-order modulators as a response to the need for higher resolutions. So far, I am not aware of smart sensor with a third-order sigma-delta modulator.

4. Examples

4.1 Smart temperature sensor

One of the successful implementations of a smart sensor is a smart temperature sensor. The state of the art is recently published at ISSCC'03 by Pertijs et al.[7]. His circuit consists of a second-order Sigma-Delta modulator and various dynamic offset-cancellation techniques. The PTAT circuit is shown in figure 16.

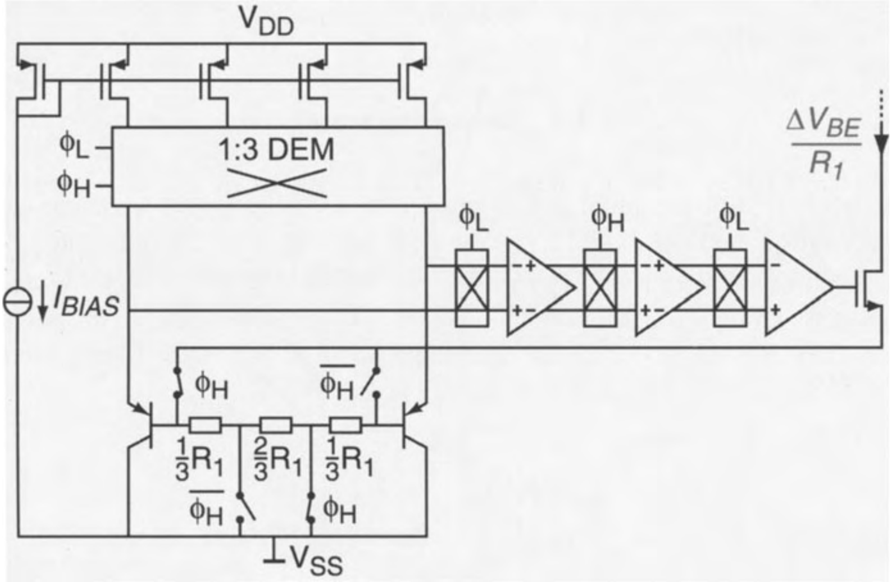

Fig. 16. PTAT circuit of high-accuracy smart temperature sensor

It won't fit in the scope of this presentation to explain all the details of this circuit, but this circuit is able to do PTAT measurements with an offset less than 1µV, which corresponds to a temperature inaccuracy of less than 0.01°C. A chip microphotograph is shown in figure 17.

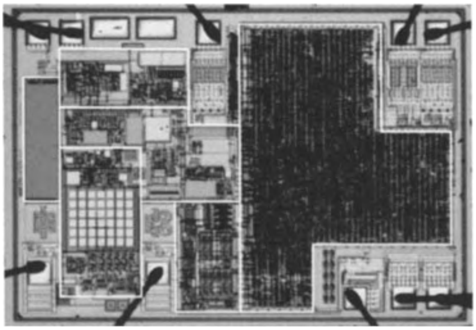

Fig. 17. Chip microphotograph of high-accuracy smart temperature sensor (Courtesy of TU Delft)

The chip measures 2.5mm^2 and is fabricated in 0.5μm CMOS. The power consumption is 430μW @10 samples/s. The accuracy is the best reported so far: 0.5°C for a temperature range from -50 to 120°C with a single calibration at 25°C. Noise is 0.03°C$_{rms}$.

4.2 Smart wind sensor

Another interesting example of a smart sensor is the smart wind sensor as proposed by Makinwa et al. [8,9]. Although this sensor has no huge market, its interface is magnificent. The principle of the sensor is shown in figure 18.

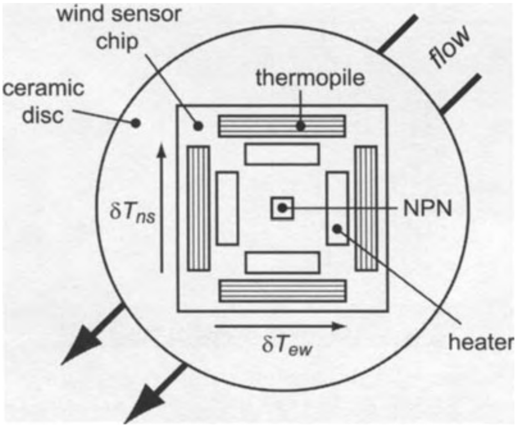

Fig. 18. Principle of smart wind sensor

The sensor consists of heaters and thermopiles that can measure temperature differences on chip. These temperature differences are a measure of the input flow. The challenge of the interface is the measurement of these tiny thermopile signals. The more accurate we can measure the sensor signals, the less power we have to dissipate to heat up the chip.

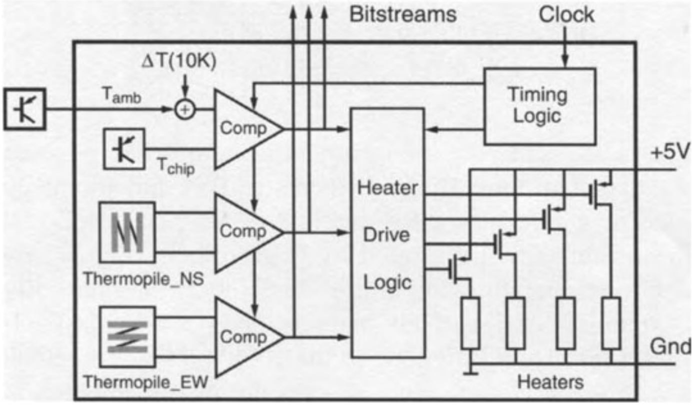

Fig. 19. Principle of smart wind sensor

The interface is shown in figure 19 and consists of three sigma-delta loops, which integrators both in the electrical and thermal domain. The comparators are autozeroed for noise and offset improvement. A chip microphotograph is shown in figure 20.

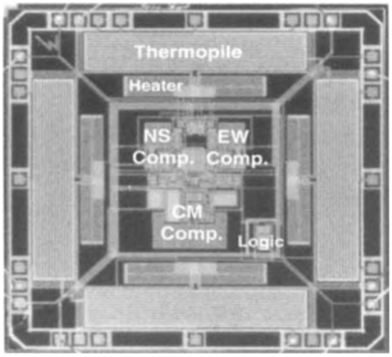

Fig. 20. Chip microphotograph of smart wind sensor (Courtesy of TU Delft)

The sensor is made in an inexpensive 1.6μm CMOS process and the interface is fully compatible with this process. Due to the small size of the interface, it perfectly fits in the center of the sensor and comes basically at zero cost. Some specifications: Temperature above ambient: 10°C, speed accuracy 5%, angle accuracy 3°, power dissipation 5mW.

4.3 Smart magnetic sensor

Magnetic sensors are widely used in industry, mainly for position and speed measurements like Anti-lock Brake Systems (ABS) and motor controls. The commonly used magnetic sensor for this is the Hall plate. Hall plates are very linear and cheap, but they are limited by huge offsets and, even worse, huge offset drift due to temperature and stress. A method to dramatically reduce the offset is the spinning current Hall plate is proposed by [10]. This method reduces the offset level of a Hall plate to the 100nV level. To be able to readout these signals with this accuracy, a nested-chopper instrumentation is developed. The principle of this amplifier is shown in figure 21.

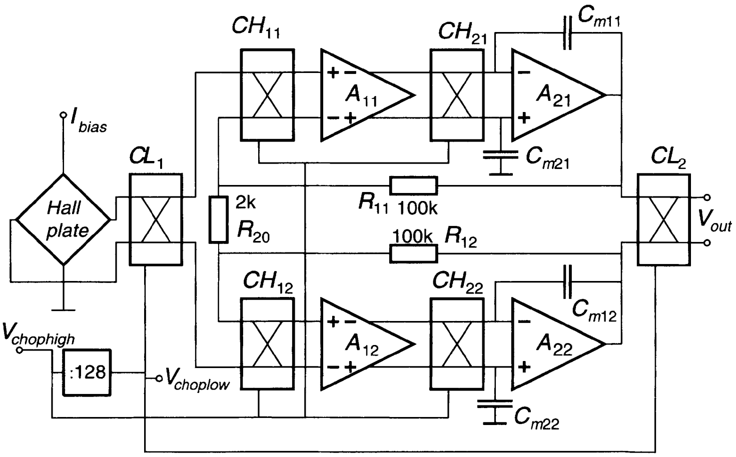

Fig. 21. Smart spinning-current Hall sensor with nested-chopper instrumentation amplifier

The instrumentation amplifier has two chopper amplifiers and is chopped at a low frequency at the outer sides to remove charge injection by the inner choppers. A photomicrograph of the smart magnetic sensor is shown in figure 22.

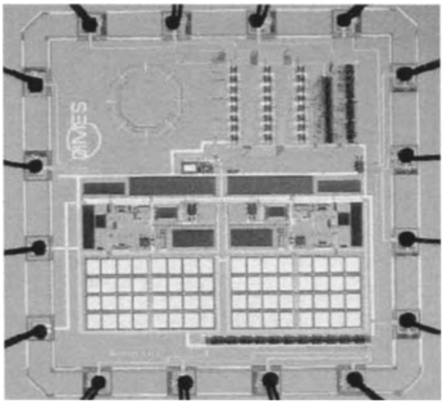

Fig. 22. Smart spinning-current Hall plate

The instrumentation amplifier has an offset of 100nV, which corresponds to a magnetic field offset of 3μT, which is approximately 10 times smaller than the earth magnetic field!

5. Conclusions

The market for smart sensors is growing approximately four times faster than the overall semiconductor market and is now approximately $1.5 Billion. Smart sensors are usually smaller and cheaper than conventional sensors and have a better reliability. In many cases, also the performance can be improved. Dynamic offset cancellation techniques are very helpful to improve the performance of the readout electronics. Of the existing dynamic offset-cancellation techniques, the chopper technique has the lowest noise. Sigma-delta ADCs are in general the best choice for digitization of smart sensor signals.

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