Detection of Defective Sensor Elements Using ΣΔ-Modulation and a Matched Filter

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Abstract

We present an integrable solution for detection of defective sensor elements using sigma-delta-(ΣΔ)-modulation and a matched filter. The sensor element is stimulated using a pseudo random binary sequence (PRBS). The sensor signal is read out and the analog output is digitized using a ΣΔ-modulator. The binary pulse density stream of the ΣΔ-modulator is the output of the sensor system and thus should ideally contains the PRBS. A matched filter has the task of detecting the pseudo random sequence in the pulse density stream and its sampled output is compared to a threshold thus making it possible to judge the functionality of the sensor element. By evaluating the magnitude of the matched filter output it is also possible to measure the sensor sensitivity. We present a discrete solution of this method, but an integrated chip using a standard 1.2µm CMOS-process has been designed and is being fabricated.

1. Introduction

Smart sensors play a critical role in many applications. While sensor failure can cause machine damage or inferior product quality, many sensors are employed in safety-critical applications and their failure could cause injury or even death of humans [1]. Hence there is a great need for dependable sensor systems. The presented concept of detection of faulty sensor elements is the key part of a dependable smart sensor system (**figure 1**). A dependable sensor system contains error detection, error analysis, error removal, and error indication functions. The error detection must be developed under aspects of real-time capability and economical costs. If an error occurs the error analysis determines the error type, error rate, and error location for the following error removal. The aim of a dependable sensor system is to obtain a sensor functionality even in the case of a fault. If a full error removal is not possible a mild or partial performance degradation may be the result.

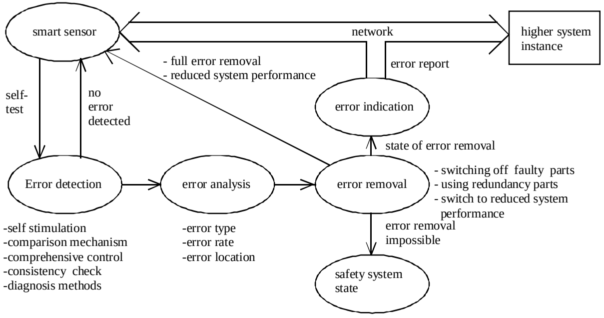

Figure 1. State diagram of a dependable sensor system

Is the error removal not possible the system has to reach its safety state. The state of the error removal must be reported to higher systems instances.

2. Error Detection Concept

The error detection plays the key role in dependable sensor systems because sensor elements are usually exposed to rough environments, no conventional self-testing strategy for non-electrical stimulation is available, and because possible sensor errors may appear “hidden“ by the following signal processing. Conventional error detection methods are based on redundancy, mathematical models of the observed process, or knowledge-based models. Use of redundancy incurs additional costs and fails when common mode failures occur. Mathematic models have problems with model uncertainties and robust detection and need complex algorithms which cannot be economically implemented in smart sensors.

Our error detection is based on self-stimulation of the sensor element combined with matched filtering for detection of the stimulation. **Figure 2** shows the block diagram of the error detection method with a temperature sensor employed as an example. The temperature sensor system includes the sensor element, the ΣΔ-modulator, and the decimator. This is complemented by the error detector containing a PRBS-generator, a heating source as the stimulator, a matched filter, and a threshold comparator for the error detection.

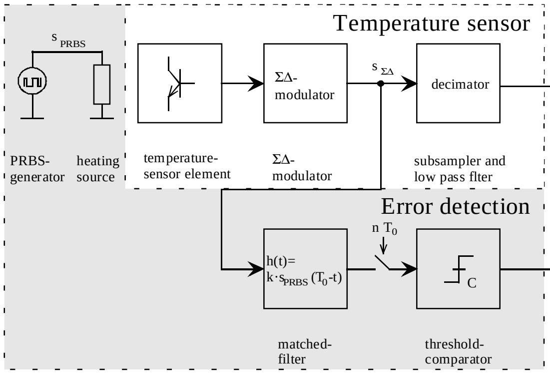

Figure 2. Block diagram of the error detection

A PRBS-generator creates the stimulus for the sensor element. Using the rect(t)-function:

$$rect(t) = \begin{cases} 1 \text{ for } |t| \le \dfrac{1}{2} \\ 0 \text{ for } |t| > \dfrac{1}{2} \end{cases}$$

the PRBS can be describe as:

$$s_{PRBS}(t) = U_0 \cdot \sum_{n=1}^{15} A_n \cdot rect\left(\frac{t - \dfrac{2 \cdot n - 1}{2} \cdot T_{Puls}}{T_{Puls}} \right)$$

with the pseudo random sequence $A = \{1;1;1;-1;1;-1;-1;-1;-1;-1;1;-1;1;1\}$. The amplitude U_0 of the PRBS can be varied for adjustment of the temperature variation ΔT_{heat} to obtain an easily detectable threshold.

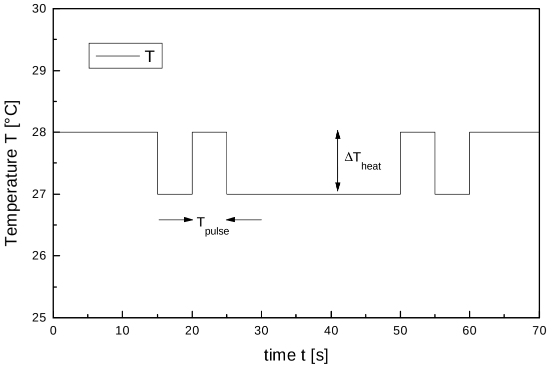

Figure 3. PRBS used for stimulation

The pulse length T_{pulse} is chosen as a trade-off between choice of the stimulation frequency and the time needed for the sensor validation. The PRBS used for the stimulation is plotted in **figure 3** as a temperature variation ΔT_{heat} of the sensor system. A resistor acts as the heating source modulated with the PRBS which converts the electrical power into a temperature variation ΔT_{heat} of the sensor system. The temperature sensor is read out and its analog output is digitized using the ΣΔ-modulator. The signal transfer function of the ΣΔ–modulator can be derived as:

$$H_{xy}(f) = e^{-i \cdot 2 \cdot \pi \cdot f \cdot T_S}$$

This means that the digitized output is delayed by a sample period T_S and contains an additional quantization noise. The output of the ΣΔ-modulator is decimated, i.e. low-pass filtered and undersampled, thus generating the digital output of the temperature sensor system.

For the error detection the ΣΔ-modulator output is fed into a matched filter which is used to detect the PRBS. A matched filter is used to reduce the amplitude of the stimulation to be detected. The use of the ΣΔ-modulator's output for the detection has the advantage of easy validation of the functionality of the sensor element and the ΣΔ-modulator. It makes a simple realization of the matched filter possible because of the use of digital signals.

The last part of the error detection concept is a threshold comparator which compares the sampled matched filter output to a prescribed threshold. According to the value of the sampled output the error status is determined. Zero values indicate a defect of the sensor element or of the ΣΔ-modulator, values between zero and the prescribed threshold indicate a reduced sensitivity of the sensor element. In the case of values greater than the prescribed threshold the sensor system shows no error.

3. System Realization

To prove the functionality of the error detection a system has been realized using an integrated temperature sensor system and some external components for stimulation and matched filter. The part of the sensor system that has been integrated in standard 1.2µm CMOS technology consists of a temperature sensor element and a first order ΣΔ-modulator. The temperature sensor consists of lateral PNP-bipolar transistors with different emitter areas [2] (**figure 4**). The difference of the base-emitter-voltage of these transistors is used as a linear temperature-dependent voltage and is converted by the ΣΔ–modulators into a pulse density binary stream.

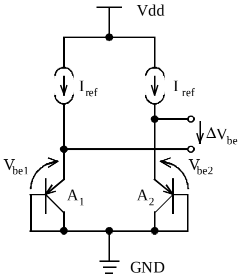

Figure 4. temperature sensor element

Note that the concept used here relies on a similar principle as analog/digital converters (ADC) based on the ΣΔ-principle. These achieve a high signal-to-noise ratio (SNR) by combining oversampling, interpolation, and noise-shaping while dispensing of the need of high precision analog components [3]. They rely on the noise spectrum of coarsely quantized input signal being shaped and shifted out of the signal band to higher frequencies to achieve fine quantization. The ADC consists of the ΣΔ-modulator followed by a decimator (**figure 5**).

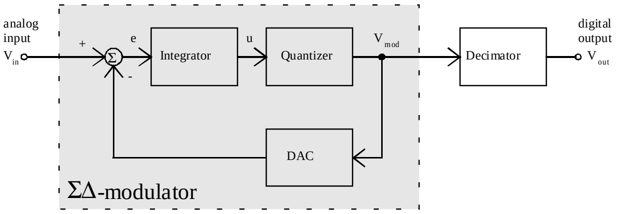

Figure 5. First order ΣΔ-converter

Typically, the analog input signal of a 1st order ΣΔ-modulator is fed into a low resolution quantizer (often just 1 bit) via an integrator, while the quantized output is fed back and subtracted from the input. This feedback forces the average value of the coarsely quantized signal to track the analog input. The modulator is followed by a decimator which is a digital low pass filter combined with a subsampler. Its task is to reduce the shaped out-of-band quantization noise and to resample the digital output down to the Nyquist rate while restoring fine signal quantization.

For the generation of a pseudo random stimulation sequence a ceramic resistor is used as a heat source. In the later complete integrated version of this error detection system a polysilicon resistor which is located near the PNP-transistors is used.

The pseudo random binary sequence is derived from irreducible codes (m-sequences) using feedback shift registers [4] (**Figure 6**). The characteristical polynomial used for the PRBS with a period of 7 is:

$$P(x) = x^3 + x + 1.$$

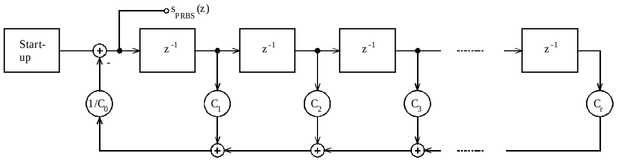

Figure 6. PRBS generator

To avoid a temperature dependence of the threshold of the sampled matched filter output a PRBS with same number of „0“ and „1“ is needed. Generators using m-sequences generate an odd-number length of the PRBS, so we use for the first half of the PRBS the non-inverting and for the second part the inverted m-sequence thus obtaining a sequence with the PRBS length of 14. Due to the low-pass character of the heat propagation in the silicon substrate we use pulse length of T_{pulse}=5s. Using a length of the PRBS of 14 every 70s is the error status updated.

The matched filter has been realized as a correlator consisting of a multiplier and a integrator (**figure 7**):

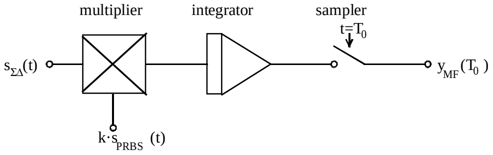

Figure 7. Matched-filter realization

Both inputs of the matched filter are digital so there is a simple realization of the correlator using an EXOR-gate for the multiplication of the two input signals $s_{\Sigma\Delta}(t)$ and $s_{PRBS}(t)$ and an up/down-counter for the integration. If both input signals are equal the counter must count up and if they are not equal the counter has to count down. At the end of the PRBS the counter is read out and its value is evaluated. In the discrete version the integrator is realized as an impulse counter Kontron K6006.

4. Measurement Results

The output of the integrated temperature sensor system is a binary pulse density stream generated by the ΣΔ-modulator, which is shown in **figure 8** for different temperatures T in the range between -40°C and 125°C. The pulse density exhibits a linear dependence on the temperature and the pulse density function Bd_{T-SDM} with T as the temperature in °C can be derived as:

$$Bd_{T-SDM} = 0.37427 + 0.00301 \cdot T \ .$$

The relatively small slope of 0.3%/°C is due to special requirements of the application for the temperature sensor and makes it difficult to detect stimulation at low amplitudes.

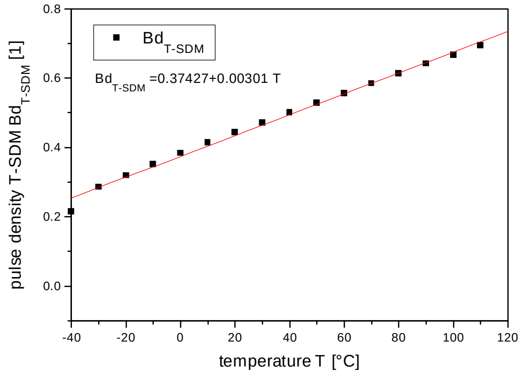

Figure 8. Pulse density of the temperature ΣΔ-modulator

By stimulation the heating ceramics converts the electrical power P_{heat} into a temperature change ΔT_{heat} of the temperature sensor. The temperature change for a constant heating power for different environment temperatures in the range between -40°C and 120°C is shown in **figure 9**:

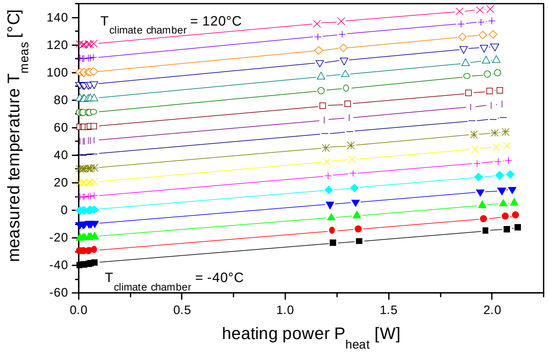

Figure 9. Temperature change caused by the heating power

The measured temperature T_{meas} raises linearly with the constant heating power P_{heat}. The measured conversion factor is R_{th}=9°C/W. This means that for a temperature rise of ΔT_{heat}=1.0°C an electrical power of P_{heat}≈0.11W is needed. In the integrated solution the heating power used to generate a temperature rise of ΔT_{heat}=1°C can be reduced to ca. P_{heat}=0.01W when using a polysilicon resistor placed near the PNP-transistors.

The simulated matched filter output is depicted in **figure 10**. The simulation results has been obtained by stimulating the input of the matched filter with the PRBS $s_{PRBS}(t)$. Every 70s at the end of the PRBS the correlation peak occurs at the matched filter output.

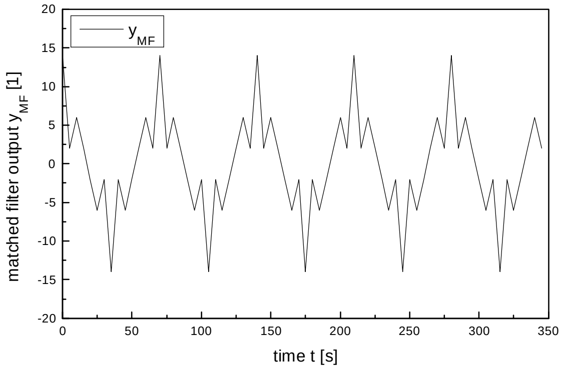

Figure 10. Matched-filter output

For the error detection the temperature sensor will be stimulated by applying the PRBS to the heating resistor. The sampled matched filter output shows **figure 11** for different heating power values:

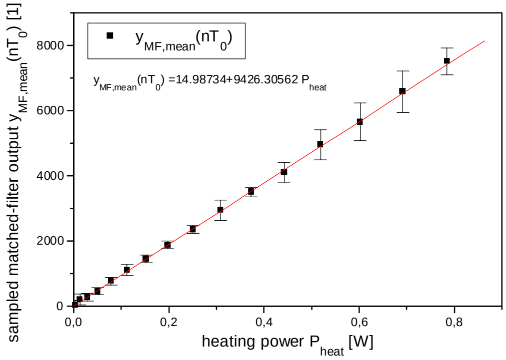

Figure 11. Sampled matched filter output

The sampled matched filter output $y_{MF,mean}(nT_0)$ can be derived with P_{heat} as the heating power:

$$y_{MF,mean}(n \cdot T_0) = 14.99 + 9426.31 \cdot P_{heat}$$

This measurement has been repeated for different temperatures in the interval between -40°C and 125°C with the same result.

The sampled matched filter output is used for the error detection of the sensor element. In the case of an faulty sensor the sampled output is ca. zero, i.e. $y_{MF}(nT_0)=0$, which is independent of the temperature. In the case of an operating temperature sensor cases the pseudo random stimulation causes a sampled output of the matched filter much greater than zero. By using a heating power of 0.1W the difference between operating an faulty temperature sensor is ca. 900. This threshold is easy to detect and results in a neglect false alarm rate. The stimulation using a heating power of P_{heat}=0.1W results in a temperature raise of ca. ΔT_{heat}=1°C which is small enough not to disturb the temperature measurement. The described error detection method is so powerful that a change of 0.3% of the pulse density of the ΣΔ-modulator can be surely detected. Using temperature systems for the same range with a maximum pulse density slope of 0.6%/°C the temperature stimulation can be reduced to $\Delta T_{heat}=0.5°C$ with the same threshold and degree of false alarm density.

The corner frequency of the heating stimulation can be determined using **figure 12** where the sampled matched filter output $y_{MF}(nT_0)$ for different heating pulse lengths T_{pulse} at two different heating powers P_{heat} is shown. The line containing triangles corresponds to the situation for heating power of $P_{heat}=0W$ and is implying no temperature stimulation or an error is the system. It is independent of the pulse length T_{pulse} and its value is $y_{MF}(nT_0)\approx 0$.

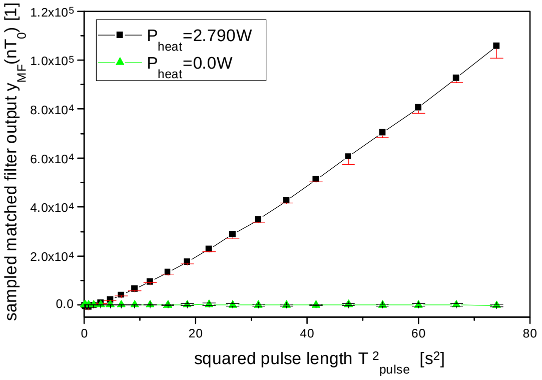

Figure 12. Sampled matched filter output

The sampled matched filter output is proportional to the power of the stimulation signal which is proportional to the squared pulse length T^2_{pulse}. For pulse length T_{pulse} smaller than 1.3s the sampled matched filter output is $y_{MF}(nT_0)\approx 0$ although the temperature sensor is stimulated. According to this result we chose a pulse length of $T_{pulse}=5s$.

5. Monolithic Integration

We have designed a complete integrated solution containing the temperature sensor, the ΣΔ-modulator, a polysilicon resistor for the heating stimulation, a pseudo random binary generator, and the matched-filter with following threshold decision. The sensor system is being fabricated in a standard 1.2µm n-well silicon-gate CMOS technology. The die area of the chip is ca. 5.7 mm^2 (**Figure 10)**. Comparing to the same temperature sensor without any error detecting the area has increased by 0.52 mm^2 due the PRBS generator, the matched filter, and the threshold decision circuitry. The polysilicon heating resistor has been placed near the bipolar PNP-transistors without an additional area consumption.

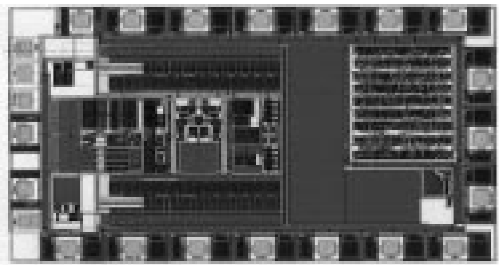

Figure 13. Layout of the temperature sensor

6. Conclusions

We have presented an error detection concept based on pseudo random stimulation of the sensor element and detection of the stimulation using a matched filter. The concept has been realized using discrete components and a temperature sensor was used as an example of the sensor element. The functionality of the error detection method has been proven. With this method it is also possible to determine the sensitivity of the sensor element. The output signal of the system yield a digitized sensor signal. When using electrical or magnetic fields for stimulation a wide variety of sensor elements can be stimulated and in this way a dependable sensor system with error detection can be built. Our next goal is to use this error detection method with a capacitive pressure sensor and applying an electrostatic stimulation. Often the bandwidth of the sensor element is higher than the desired measurement bandwidth, so it is possible to avoid any interference with the measurement by choosing a frequency for the PRBS outside of the measurement bandwidth. A full integrated solution of this error detection concept has been designed and is being fabricated.

7. References

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