High-end sensors: challenges for the future

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Abstract. The paper describes the coming challenges in high-end sensors and transducers design. These challenges are coming from the recent technological limitations in microelectronics. The proposed approach to overcome such limitations is based on programmable parameter-to-frequency converters as a digital sensor’s core and advanced method of measurement in order to move from a traditional analog-to-digital conversion to alternative frequency (period, duty-cycle, time interval)-to-digital conversion. Working in the frequency-time signal domain simplifies design, and obviates some technical and technological problems, due to the properties of frequency as informative parameter of sensors and transducers. The major benefits offered by such approach are high reliability, high metrological performance, wide functionality, cost effectiveness and scalability. The perspectives, which will bring such approach to various sensors and transducers for physical and chemical, electrical and non-electrical quantities are illustrated by examples of multivariable sensors, sensors for smart health care and wearable sensors.

1. Introduction

Further technical progress in microelectronics, instrumentation, robotics, automation control and systems requires the design and development of various high-end sensors and sensor systems on its basis for different physical and chemical, electrical and non-electrical quantities. In addition, high-end sensors will play significant role in the coming IoT 2.0 and Industry 4.0 trends.

High-end sensors are advanced detecting devices, which have high metrological performances and technical (operational) characteristics. Recently, the functionality extension, namely, self-testing, self-validation and self-adaptation are also observed in some high-end sensors. This trend along with the increase of metrological performances will prevail in the next few years in the field of high-end sensors and sensor systems on its basis.

Speaking about the high-end sensors and transducers, the basic metrological performances are the following: specified measuring range; measuring time, and various components of error of measurement. Namely metrological performances directly affect the cost of high-end sensors, transducers and sensor systems. So, for example, increasing the accuracy of a sensor in two times, can cause an increase in cost in 10 times. In order to make high-sensors that would meet modern requirements and at the same time have a reasonable price, new technologies that are cutting costs while increasing effectiveness are necessary.

The best metrological performance of high-end sensors can be achieved by using the frequency as the output informative parameter of the sensor, and the subsequent use of a frequency-to-digital
converter (FDC) when creating digital sensors based on its basis. Such sensors have undeniable advantages over voltage, current and digital output sensors based on analog-to-digital converters (ADC) due to the well-known frequency properties as an information parameter of the sensor signals: high noise immunity; high power signal; wide dynamic range; high accuracy of reference; simple interfacing, integration and coding, and multiparametricity.

There are many frequency, period, duty-cycle, pulse width modulated, time interval and pulse number output sensors on the modern sensor market [1].

2. State-of-the-art and technology challenges
The first frequency output transducers (string distant thermometer and tensometer) and time-to-digital converter (TDC) – the ADC for the narrow time intervals, have developed and patented in the Former USSR in 1930, 1931 and 1941 respectively [2-4].

In 1961 professor P. V. Novitskiy wrote: "... In the future we can expect, that a class of frequency output sensors will get such development, that the number of now known frequency output sensors will exceed the number of now known amplitude sensors..." [5]. It was also predicted in a technology forecast in 1971: "Many basic measurements will be related to or measured by time/frequency techniques. This situation will occur because of the increasing facility and accuracy provided through time frequency measurements... Frequency and computing counters can be expected to become smaller, lighter and cheaper, provide direct frequency readout and will be more universally used... Progress will continue in the field of time and frequency during the next five years and will contribute materially to the state of the art in electronics” [6].

Despite the fact that this forecast was not fully justified till now, it is really the situation when “the future glimmers long before it comes to be”. Today, the next big challenge has come from microelectronics. So, in 2010 professor Stephan Henzler did write: “Below the 100 nm technology node the design of analog and mixed-signal circuits becomes perceptibly more difficult. This is particularly true for low supply voltage near 1 V or below” [7]. The result is not only an increased design effort, long development time, high risk, cost and the need for very high volumes [8] but also a growing power consumption [7].

There are many reasons that analog doesn’t scale as readily [9]. The area shrinks considerably less than predicted by the digital scaling factor. Obviously, both effects are contradictory to the original goal of scaling. However, digital circuits become faster, smaller, and less power hungry [7]. The fast switching transitions reduce the susceptibility to noise, e.g. flicker noise in the transistors. There are also a few drawbacks, such as the generation of power supply noise or the lack of power supply rejection. Because of these drawbacks the analog circuits do not become much smaller in area in smaller technologies.

In the saturation region, there is a much larger change in current in 40 nm process in comparison with the 130 nm process. This change leads to the fact that the transistor has much less control over the current. The design of critical analog circuits that don’t scale easily, for example, amplifiers, analog front ends and ADCs, is therefore much more difficult, as the realizable gain per stage is significantly reduced. To compensate for that reduction, more sophisticated circuits are required, leading to lager area and higher consumption [9].

Another factor is the reduced supply voltage and dynamic range. As the supply voltage is reduced with the migration to lower process nodes, the available signal range shrinks. This lower signal range requires proportionately lower noise levels to maintain the same dynamic range. In mixed-signal circuits, such as ADCs using switches capacitors, the reduction in the noise level can be achieved with larger capacitors. To compensate for a 2X reduction in signal range, the capacitors must be increased 4X – making it quite difficult to scale down the area. In addition, the larger loading capacitances require larger currents for charging and discharging, invariably leading to higher consumption. In addition, the designs will become more complicated in order to yield good performance at those low voltages [9].

Their power consumption and speed performance improve significantly due to reduced parasitic capacitance. On the other hand, this results in major challenges for the design of interface electronics:
matching and noise becomes a serious issue, while the dynamic range is reduced due to the supply voltage reduction [10].

The scaling for the analog/mixed ICs can be achieved using a number of different design techniques, not using design CAD tools but rather different architectures. At 28 nm, second- and third-order effects have become serious concerns. As a result, existing design and verification techniques are starting to fall short. Smarter solutions are needed to manage issues arising from tighter spacing [11].

However, digital circuits become faster, smaller, and less power hungry and are scaled very well with scaling CMOS technologies. So, another trend is the transition of traditional analog functions to the quasi-digital domain, for example, to use a frequency (time)-to-digital conversion instead of analog-to-digital conversion, and implement as many system components as possible in the digital or quasi-digital domain. It lets get over technological limitation at scaling.

Frequency/time domain signal processing and so TDC and especially FDC converters are well suited for high volume microelectronics in order to circumvent analog impairments in nanometer-scale CMOS technologies. In principle TDC only consist of sampled delay-lines. The challenges arise when continuous measurement, long time intervals, high resolution, linearity, low power consumption and robustness come into the play. The architectures addressing one or more of these issues rapidly become more complex [7]. The TDC can exploit some advantages of digital circuits but still behaves like a mixed-signal circuit. Hence, only the FDC concepts are promising that have the ability to exploit fully the advantage of digital circuits [12]. The FDC will be a trend-setting technology for ultimately scaled CMOS technologies in the nearest future, and can be used for many applications such as smart digital sensors, IoT and Industry 4.0.

3. Advanced FDC for digital high-end sensors, transducers and sensor systems

Nevertheless the frequency measurement technique is well established, converting frequency to a digital world for real time systems is not an easy task. For a long time this task was complicated by the absence of any standard peripheral integrated circuit chip for this application. From the other side to meet all the above requirements for smart high-end sensors, modern FDC must be based on advanced frequency-to-digital conversion methods. Only the advanced method can guarantee the low and constant quantization error in all specified frequency range; wide dynamic range (130 dB and more), and non-redundant conversion time. Such measuring technologies (the patented methods and ICs of FDC) were introduced by the F2D, Ltd. (Ireland) – the IFSA Group company, and realized in their series of integrated circuits, suitable for various physical and chemical smart digital high-end sensors and sensor systems.

The integrated Frequency-to-Digital Converters of USTI Series of IC (Figure 1) have the wide frequency range from 0.05 Hz to 9 MHz without prescaling and up to 144 MHz with prescaling, selectable relative error from ±1 to ±0.0005 %. The ICs can convert to digital 26 different frequency-time parameters of signal including rotational speed, resistance, capacitance and resistive bridge values. The conversion time is non-redundant and lets to design various high-end sensors, transducers and sensor systems with intelligent features, such as self-adaptation to select appropriate accuracy, conversion time or power consumption. The ICs have I2C, SPI and RS232 popular interfaces.

The FDC and frequency output sensing elements, as well as voltage output sensing element, voltage-to-frequency converter (VFC) and FDC can be integrated into a single chip or System-on-Chip (SoC). The proposed design approach lets eliminate the mentioned above technological limitations because of the FDC is pure digital component, which can be easily realized in a standard CMOS technology below 100 nm.
4. Perspectives and applications
Nevertheless the described sensor technologies open a lot of various sensor related markets, let focus on following:

- Sensors for smart health care;
- Multivariable sensors for physical and chemical quantities;

4.1. Sensors for smart health care
There are big expectations for the potential of Smart Health Technologies to support healthcare. This type of technology is still in its infancy, but Smart Health Technologies are expected to be commonplace in the future. However, further research and development is needed, e.g. to ensure the accuracy of data [13].

According to the recent market report published by Persistence Market Research, titled 'IoT Sensors in Healthcare Market: Global Industry Trend Analysis 2013 to 2017 and Forecast 2018–2026', the global IoT sensors in healthcare market was valued at US$ 2,208.9 Mn in 2017, and is expected to register a CAGR of 12.2% from 2018 to 2026 [14]. Improvements in patient engagement, increased accuracy in data analysis, enhanced disease management and treatment results, and reduction in treatment costs are major factors driving the growth of the global IoT sensors in healthcare market. However, privacy concerns and adherence to standard regulations, and varying communication protocols in different IoT sensors in healthcare equipment, hinder the growth of the global IoT sensors in healthcare market. Some of the recent trends for the IoT sensors in healthcare market are focus on implementation of artificial intelligence and IoT technologies, and the increasing demand for wearable devices in the IoT sensors in healthcare sector [14].

The common sensors used in smart healthcare are the following: temperature sensors, ECG, blood pressure, blood glucose, EMG, heart rate, SpO₂, gyroscope, motion sensors, and accelerometers [15]. Things-oriented architectures need to be adaptive based on the application, real time monitoring, on-time delivery, higher sensitivity, maintain higher efficiency at lower power dissipation, and embark on intelligent processing [15]. Combining sensors, actuators, microcontrollers, processors, along with cloud computing, the IoT helps in getting accurate results and makes healthcare attainable to everyone.

Wearables, especially in the form of smart watches or bands, have been revolutionizing the market. Significant amongst the healthcare products are smart watches. Smart watches are becoming more ubiquitous. The projected annualized rate is expected to reach 70 million units at a growth of 18% annualized rate by 2021 [15]. Recommended sensors are those that measure the vital signs - pulse, respiratory rate, and body temperature - as these are the essential signs for determination of critical health. Further sensors that could be implemented are blood pressure and blood oxygen sensors, as these parameters are often taken alongside the three vital signs. Special-purpose sensors such as blood-glucose, fall detection, and joint angle sensors could also be implemented for systems targeting a specific condition [16].

The perspectives to usage of such digital sensors based on the FDC lets to achieve a lower cost, which is one of the main requirements for any IoT sensor. Also, the use of so-called self-adaptive sensor
systems based on FDC with an accuracy/power consumption trade-off can reduce the power consumption in several times [12].

4.2. Multivariable sensors for physical and chemical quantities

Multivariable sensors sometimes are called ‘multifunctional sensors’ or ‘multiparametrical sensors’ [12, 17]. Multivariable sensing capability enhances operations by measuring several physical or chemical quantities by a single device. There are many multivariable sensors on the market, for example, temperature, absolute and differential pressure multivariable transmitter (Rosemount 3051S) from Emerson; multivariable mass flow meter (PanaFlow MV82) with temperature, velocity and pressure measurements (Baker Hughes a GE company); pressure and temperature transducers with two square waves outputs from Parascientific (USA); multivariable pressure and temperature transducers QHB, SPB, QMB from Quartzdyne with two frequency outputs, and others. GE has also proposed chemical and bio multivariable resonant sensors for environmental, industrial, and security applications [18].

However, the most perspective multivariable sensors are sensors with a frequency output because of one, single sensor’s output (pin) can contain information about two sensing variables: one of which is proportional to the frequency, and second – to the duty-cycle of rectangular pulse output signal. For example, in the optical sensor developed in Delft University of Technology the pulse frequency proportional to the optical intensity (luminance) and the duty cycle to the colour (chrominance) [19].

Another example of quasi-digital, multifunctional, multiparametric sensor is described in [20]. This piezoresistive pressure sensor has one output with frequency proportional to pressure and duty-cycle proportional to temperature.

The multivariable sensor for humidity, pressure and temperature is described in [21]. The system has three frequency outputs with a single informative parameter for each of the outputs.

The perspective multivariable sensors can be easy designed based on several frequency output sensing elements and digital multiplexer. In comparison with the analog multiplexed the last one is cheaper and does not introduce any addition error.

5. Conclusions

Today the most advanced high-end sensors, transducers and sensor systems for various physical and chemical, electrical and non-electrical quantities can be built on the novel frequency-to-digital converters, which are based on advanced methods for frequency-to-digital conversion.

Working in the frequency-time signal domain simplifies design, and obviates some technical and technological problems, due to the properties of frequency as informative parameter of sensors and transducers. The major benefits offered by such approach are high reliability, high metrological performance, wide functionality, cost effectiveness and scalability. So, time has come to manufacture high-end sensors.

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