High-End Sensors & Sensor System: How to Achieve High Metrological Performances?

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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 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 metrological performances 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 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.

Depending on the output signal, all sensors are divided into three main groups: sensors with analog outputs (voltage and current), quasi-digital sensors (frequency, period, duty-cycle, pulse number, phase shift, pulse width modulated (PWM) output) and digital output sensors, which have to various buses and interfaces (Fig.1 a, b). The last one is based on the first two groups using Analog-to-Digital Converters (ADC) or Frequency-to-Digital Converters (FDC).

![Fig.1. Sensors outputs (a), and (b) quasi-digital output sensor types (IFSA study 2017).](image-url)
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 FDC when creating digital sensors based on its basis. Such sensors have undeniable advantages over voltage, current and digital output sensors based on 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;
- Simple integration and coding;
- Multiparametricity.

There are many frequency output sensors on the modern sensor market (http://www.sensorsportal.com). Let’s consider some examples with high metrological performances in details. The Quartzonix™ Digital Pressure Standard Series 960 from Pressure Systems (Fig. 2 a) are designed for use as a precision pressure transducer where the highest levels of traceable accuracy and stability are required. Quartzonix™ pressure standards use a patented monolithic quartz resonator to achieve unparalleled accuracy and stability. Pressure is measured via a change in the resonant frequency of an oscillating quartz beam by pressure induced stress. Quartzonix™ pressure standards produce an output frequency between 30 and 45 kHz and can achieve a full-scale pressure resolution of ± 0.0001%. The units provide conformance to a calibration curve of better than ± 0.01% FS and have long-term stability of ± 0.01% FS over a six month period.

**Fig. 2.** Accurate pressure transducer Quartzonix™ Digital Pressure Standard Series 960 (a), and Digiquartz® Submersible Depth Sensors Series 8000 (b).

Digiquartz® Transducers D50 Series 8000 form Paroscientific, Inc. are incorporated into submersible housings as depth sensors. All depth sensor ranges are available with frequency outputs. Typical application accuracy is better than ±0.01% with parts-per-billion resolution, low power consumption, and excellent long-term stability. Absolute Pressure Transducers D25 Series 2000, 3000 and 4000 from the same company has the same accuracy ±0.01% (Fig. 3 a, b).

Fast-response, frequency output, extremely low-drift temperature sensor SBE 3plus from SEA-Bird Scientific (Fig. 4) has initial accuracy ± 0.001 °C and full scale relative error ±0.003 %. The glass-coated thermistor bead, pressure-protected in 0.8 mm diameter thin-walled stainless steel tube. Exponentially related to temperature, the thermistor resistance is the controlling element in an optimized Wien Bridge oscillator circuit. Resulting sensor frequency is inversely proportional to the square root of the thermistor resistance and ranges from approximately 2 to 6 kHz, corresponding to -5 to +35 °C. The sensor can be
used in custom oceanographic systems or for high-accuracy industrial and environmental temperature monitoring applications.

Such sensors as light and colour sensors from *ams*, *Melexis* and *Hamamatsu* have a wide frequency ranges from part of Hz to some MHz. All rotational speed sensors and rotational acceleration sensors have a wide frequency range: from 0 Hz to tens of kHz. All chemical sensors and biosensors based on quartz crystal microbalance have frequency outputs, and that field needs accurate frequency measurements with high resolution.

![Absolute Pressure Transducers 25D Series 2000 (a) and 4000 (b).](image)

**Fig. 3.** Absolute Pressure Transducers 25D Series 2000 (a) and 4000 (b).

![Temperature sensor SBE 3plus.](image)

**Fig. 4.** Temperature sensor SBE 3plus.

In order to use such high-end sensors in IoT, digital control systems and DAQ systems, the accurate FDC must be used in the digital output sensor design. This device directly influences the sensor metrological characteristics, such as accuracy and conversion time, as well as power consumption. The advanced design approach is based on *Excelera*’s technology and consists either in the usage of intermediate high-end voltage-to-frequency converter (VFC) and frequency-to-digital converter (FDC) in the case of analog output sensing elements, or based on only the integrated FDC in the case of quasi-digital sensors. All this means that it is necessary to use frequency-to-digital conversion based on the advanced measuring method, because standard counting methods cannot meet the high metrological level of modern high-end sensors due to a lot of disadvantages: narrow frequency range; dependence of quantization error on the frequency range; and redundant conversion time. This problem has been solved by *Excelera, S.L.* due to their advanced, patented method for frequency-to-digital conversion.

The integrated Frequency-to-Digital Converters USTI Series of IC (Fig. 5) from *Excelera* have wide frequency range from 0.05 Hz to 9 MHz without prescaling and up to 144 MHz with prescaling), configurable relative error from $\pm 1$ to $\pm 0.0005 \%$. The ICs can convert to digital 26 different frequency-time parameters of signal including rotational speed; and resistance, capacitance and resistive bridge values. The conversion time is non-redundant and lets to design various high-end sensors and sensor systems with intelligent features, such as self-adaptation to select appropriate accuracy, conversion time or power consumption. The ICs have IIC, SPI and RS232 interfaces.

The FDC and frequency output sensing elements, as well as voltage output sensing element, VFC and FDC can be integrated into a single chip. This lets to overcome the existing technological limitations: below the 100 nm technology, the design of analog and mixed-signal circuit becomes perceptibly more difficult. Such analog components are not "process compatible". This is particularly true for low supply voltage near 1 V
or below. The result is not only an increased design effort, long development time, high risk, cost and the need for very high volumes, but also a growing power consumption, lost performance and flexibility. But the proposed design approach lets eliminate these technological problems because of FDC is pure digital component, which can be easily realized in standard CMOS technology.

**Fig. 5.** Integrated Frequency-to-Digital Converters (UFDC and USTI Series of IC) and Development Board (*Excelera, S.L.*).

Working with the frequency as informative parameters of sensors significantly simplifies design, and obviates recent technical and technological problems, due to the physical properties of frequency signal. The major benefits offered by such approach are high reliability, high metrological performance, wide functionality, cost effectiveness and scalability of modern high-end sensors.
Universal Sensors and Transducers Interface (USTI-EXT) Series of IC for Automotive Applications

- Precision measurements of frequency-time parameters of sensor outputs
- rpm measurements
- Cx, Rx and Resistive Bridges measurements
- Extended temperature range from -55 °C to +150 °C
- I²C, SPI and RS232

http://www.sensorsportal.com/HTML/E-SHOP/e-shop_4.htm