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Sensors Systems for Smartphones, Tablets and IoT: New Advanced Design Approach

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Abstract: An advanced, novel sensor systems design for smartphones, tablets and IoT is described in this article. Coming technological limitations and challenges are outlined, and new design approach for such mobile devices is described in details. The design is based a smart system integration and a novel Series of IC - Universal Sensors and Transducers Interface (USTI-MOB) developed by the authors. It allows to eliminate existing technological limitations and lets to create various multisensor systems with high metrological performance quicker and easily to make mobile devices smarter. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Sensor system, Universal Sensors and Transducers Interface, Smartphone, Quasi-digital sensors, IoT, Multisensor systems, USTI-MOB

1. Introduction

Modern mobile devices market is a high growth and potentially huge market. According to data from the *International Data Corporation (IDC)* the worldwide smartphone market grew 28.2% year over year in the fourth quarter of 2014 (Q4), with shipments of 377.5 million units [1].

Research and Markets predicts that the global tablets market to grow at a CAGR of 8.5% over the period 2014-2019 [2]. The same company also reports that the global Internet of Things (IoT) market to grow at a CAGR of 31.72% over the period 2014-2019 [3]. According to the report, the growing number of smart connected devices has resulted in an increase in the demand for the IoT worldwide. Also, 25 billion devices are expected to be connected to the internet by 2015 and 50 billion by 2020, as predicted by *Cisco's* IBSG [3]. IoT devices are focused on sensing and actuating of physical environment. While the IoT represents the convergence in advances miniaturization, wireless connectivity, increased data storage capacity and batteries, the IoT wouldn't be possible without sensors. Sensors detect and measure changes in physical world and they are necessary to turn billions of objects into data-generating "things" that can report on their status, and in some cases, interact with their environment [4]. A common requirement for IoT end nodes is the need for small size since these devices are typically constrained to a very small footprint: for example, in wearable devices a small size and small weight are critical for customer acceptance.

A *Consumer Electronics Association (CEA)* representative at a press conference on Consumer Electronics Show (CES' 2013) in Las Vegas (USA) said that the technology industry has entered the "post-smartphone era" when communication functions such as calls and texting are no longer the main focus for smartphones. The representative noted that smartphones now mainly are used for non-communication types of functions. CEA also said that consumer electronics products are becoming "sensorized" - i.e., devices like smartphones and tablets are making increasing use of sensors that allow the digitization of everyday things.

In terms of functionality, sensors continue to improve significantly. Future smart devices (smartphones and tablets) will include new sensor types, such as biometric, pressure, and environmental sensors, along with a few sensors currently in most smartphones [5]. More sensors and the great penetration of mobile devices will drive global sensor shipments to 6 billion units by 2015, 1/3 of which will represent new sensor types [6].

Modern smartphones have a limited number of built-in sensors. As rule, it is so-called "must have" sensors, mentioned above (accelerometer, gyroscope and magnetic sensors), and in several models, there are also light (proximity) and pressure sensors. But based on the *International Frequency Sensor Association (IFSA)* survey 2012 "What Sensors are Needed in a Mobile Phone ?" 36 % of responders from 265 would like to have much more sensors in their mobile devices [7]. First of all it is various gases detectors, air quality detectors, temperature, humidity, altitude and ultra-violet sensors.

Among other suggestions, responders mentioned also radiation and glucose sensors, fire alarms, alcohol detectors and breath analyzers. Several other emerging sensors have been identified, with the potential to become new killer applications in 5 to 10 years: environmental sensors, fingerprint sensors, etc.

Smartphones and tablets users expect their devices to be intuitive and capable of interacting without pressing a button. Sensors make this possible.

2. Sensor Systems Design Approaches

2.1. Smartphone and Tablets Sensors Classification

Based on a system design and communication features all sensors for smartphones and tablets can be divided into two main groups: built-in (embedded, internal) sensors and external sensors (Fig. 1).

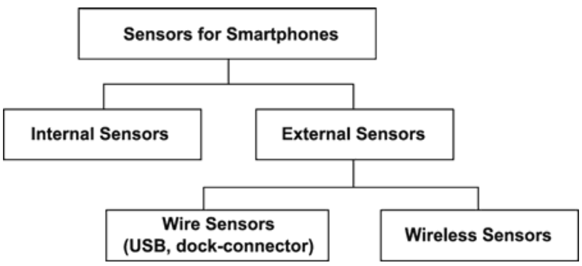

Fig.1. Smartphone and tablets sensors classification.

In turn, the external sensors can be divided into two main subgroups: wire sensors (physically connected to a USB port or dock-connector) and wireless sensors (connected by Bluetooth with a wearable sensing module, for example). It is clear that the best solution should be to use the internal sensors if possible.

2.2. Technological Limitations

Dependent on type of sensors output and informative parameter, only two types of sensor outputs are used till now in modern smartphones and tablets: analog output (voltage) and digital output (SPI and/or I2C sensor buses). This fact strongly limits possibilities of smart system integration for mobile devices and IoT.

Sensors usually are analog output devices. To input information from such sensors to system microcontroller or application processor in smartphones and tablets it is necessary to convert analog output signal to digital with the help of analog-to-digital converter (ADC). Taking into account a low power analog signal on sensors' outputs, it is necessary to use also an analog amplifier and filter. But below the 100 nm technology, the design of analog and mixed-signal circuit becomes perceptibly more difficult [8, 9]. 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 increased design effort, long development time, high risk, cost and the need for very high volumes, but also growing power consumption, lost performance and flexibility.

Digital circuits, however, become faster, smaller, and less power hungry. They scale very well with scaling CMOS technologies. Their power consumption and speed performance improves significantly due to reduced parasitic capacitance. On the other hand, this results in challenges for the design of interface electronics: matching and noise become a serious issue, while the dynamic range is reduced due to the supply voltage reduction. 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. Still, the advantages are overwhelming and suggest implementing as many system components as possible in the digital or quasi-digital domain. However, regarding sensors and transducers, the number of physical phenomenon, on the basis of which direct conversion sensors with digital outputs can be designed, is essentially limited. There is no natural phenomenon with discrete performances changing under pressure, temperature, etc. In this case, an ADC and analog multiplexers (for sensor arrays, multisensing and multi-parametric systems) are used. However, since scaling technology results in higher device speeds, the improved timing and frequency resolution at ADC conversion can be achieved when the analog signals are transformed into impulse signals. When going to smaller technologies reduced parasitic gate capacitances result in smaller gate delays. This improved frequency/time resolution makes frequency (time)-to-digital conversion an interesting and promising alternative for ADC converters. Based on all the above, and existing standard CMOS technological 90 nm, 65 nm, 45 nm, 32 nm, 22 nm, 19 nm and 14 nm processes, a main challenge has arisen to changing a traditional analog (voltage) informative sensor parameters to a quasi-digital (frequency-time) parameters in order to eliminate difficulties and limitations of analog and mixed-signal circuits design below 100 nm.

Today, more and more manufacturers propose digital output sensors for smartphones and tablets with SPI or I2C output, but they are based on a standard ADC, and all mentioned design problems including the low level of smart system integration can not be eliminated by this way.

How to solve these design problems and create sensors systems for smartphones, tablets and IoT with high metrological performances, wide functionality and process compatibility ? First of all it is necessary to create a core (a new component) for smart sensor systems: programmable, universal, high-performance frequency (time parameters)-to-digital converters (FDC) instead of traditional ADC. This unit directly influences such sensor metrological characteristics, such as accuracy and the conversion time, as well as power consumption. It is clear that such FDC must be based on novel, advanced methods of measurement for frequency-time parameters of signals, and two different design approaches at the same time: technological and structural-algorithmic approaches that open a way towards radically new forms and uses of nano- and microelectronic technologies for bridging smart sensors and system integration.

The challenges arise also when high resolution, linearity, low power consumption, high dynamic range, reliability and robustness come into the play. Hence, the only promising FDC concepts are those which have the ability to exploit the advantages of digital circuits. The FDCs have the potential to become trend-setting technology for recently and future scaled CMOS technologies for both the monolithic approach (System-on-Chip (SoC), System-in-Package (SiP)) and multi-chip approach to drastically increase the system integration level. It opens great perspectives for application of such technology in modern and future mobile devices.

In alternative design approach, frequency-time parameters of electrical signal instead of voltage or current must be used as informative parameters on a sensor’s output. First of all it is frequency, period, duty-cycle, pulse-width modulated signs, phase-shift, pulse number, etc. In such so-called quasi-digital sensors these informative parameters are proportional to measurand, and FDC should be used to obtain a digital output. According to the *International Frequency Sensor Association’s (IFSA)* 2012 study, quasi-digital sensors share approximately 20 % of the modern global sensors market and among them frequency output sensors share 70 % [7]. Today there are quasi-digital sensors and transducers for any physical and chemical, electrical or non-electrical quantities on the modern market [7]. In addition, any voltage signal on any analog output sensors can be easy converted into a frequency signal with the help of integrated, low cost voltage-to-frequency converter [10].

Frequency-time output (or quasi-digital) sensors are rather interesting from a technological and fabrication compatibility point of view, due to the simplifications of the signal conditioning circuitry and measurand-to-digital converter, as well as metrology performances and the hardware minimization for realization. The last one essentially influences the chip area. Moving from the traditional analog (voltage and current) informative parameters to the frequency-time parameters lets us achieve many well known and validated benefits due to properties of frequency, such as the informative output signal for sensors and transducers [8], namely:

- High noise immunity;
- High output signal power;
- Wide dynamic range;
- High accuracy of frequency standards;
- Simplicity of signal switching and interfacing;
- Simplicity of signal integration and coding;
- Multiparametricity;
- Modern process compatibility.

Using frequency as the output signal for sensors is an extremely useful alternative to the conventional analog voltage output signal and is easily accomplished with relatively few components. By eliminating the need for an ADC, frequency output sensor schemes reduce the cost of sensor systems and increase the level of system integration. No output standardization is necessary as in the case of analog signals. Many types of sensing elements and read-out circuitry can be merged by this way on a single chip, in SoC or SiP. In addition, such approach provides a great opportunity to create new self-adaptive smart sensors and sensor systems for the future smartphones, tablets and IoT.

A duty-cycle output signal is also widely used as an information-carrying parameter for different quasi-digital sensors. It is quite immune to interfering signals, such as voltage spikes, and the ratio between time intervals does not depend on the absolute value of any component.

The state-of-the-art review of modern quasi-digital sensors has shown the obvious tendency of the relative error decreasing up to 0.003 % and below [7, 8]. These devices are working in broad frequency ranges: from several hundredth parts of Hz up to several MHz. The extension of their "intelligent" capabilities including intelligent signal processing is traced.

2.3. Traditional Design Approach: State-of-the-art

The importance of microsystems is continuously growing because of the combination of two trends: the progress in silicon sensor technology and the introduction of new techniques for interface circuits. The cost of sensor systems has been greatly reduced due to the batch fabrication of both the sensors and the interface circuits. Interface circuits are the most critical part of the signal processing chain, which means that the overall performance of the system strongly depends on the quality of the parameter-to-digital converter.

As part of its signal processing, the fully integrated 6-axis motion processing solution proposed by *InvenSense, Inc.* (Fig. 2) has fixed-frequency anti-aliasing filters as part of its ADC block, followed by programmable digital low-pass filter, which negate the need for external signal conditioning and microcontrollers. Nevertheless that this solution uses smart sensors, it has a disadvantage: analog components as ADCs and analog multiplexers. These components mean mixed design. The analog multiplexer also introduces an additional error of measurements, and ADC as rule has a limited (by power supply and noises) resolution and dynamic range. In addition, this solution is not compatible with the modern and future technological processes and effective system integration approach. In order to achieve acceptable metrological performance, complex sensor fusion algorithms must be used [11, 12].

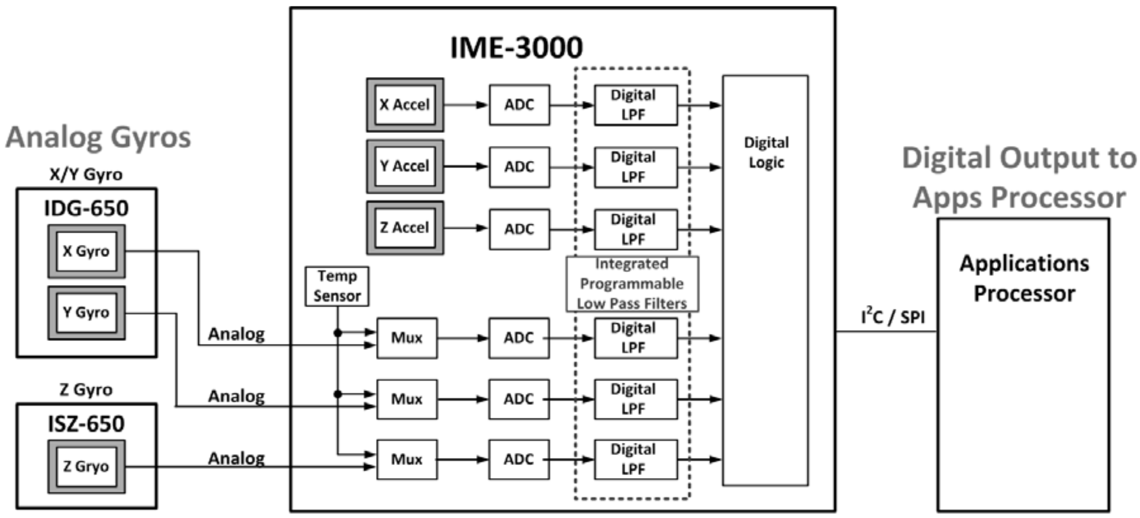

Fig. 2. Integrated 6-axis motion sensors processing solution.

A Unified MEMS sensor interface development is described in [13]. A standards development group is exploring the feasibility of a new interface standard that would enable even multiple degree-of-freedom arrays of MEMS sensors to use a simple common interface. Such an interface—which would be used by accelerometers, magnetometers, gyroscopes, altimeters, compasses, proximity sensors and non-MEMS sensors. A two-wire interface standard as an example of how up to 23-pins from a SoC could be eliminated with a universal multi-drop interface - a kind of network-for-sensors, instead of using I2C or SPDIF [13]. This would greatly simplify the design and cut the bill-of-materials cost of mobile devices with many of sensors. Of course, such solution will be possible if sensors vendors will support a common standard. In addition, this design uses ADCs, and is in the front of coming technological limitations, discussed above.

A design solution for digital sensor systems can be based on the ultra-low power, compact sensor hub microcontroller for smartphones ML610Q792 - the industry's smallest microcontroller from *LAPIS Semiconductor* (formerly *OKI Semiconductor*) a ROHM Group company, designed for integrated, low-power control of multiple sensors in smartphones [14]. Remarkably low power consumption not only prolongs battery life, but enables support for wireless communication in compact products like pedometers and smartphone accessories. The sensor hub microcontroller is working with analog and digital (RS232, SPI and I2C) sensors. However, it is not possible to use it with quasi-digital sensors. In turn, digital sensors are based on standard ADCs, and therefore have many disadvantages mentioned above.

Many sensors companies have introduced various digital output sensors suitable for smartphones and tablets. One of the recent examples - an integrated barometric pressure sensor is shown in Fig. 3. It is based on the traditional design approach for digital sensors and contains ADC, analog front end, filter, and DSP. Clear, the level of system integration is quite low due to the mixed design.

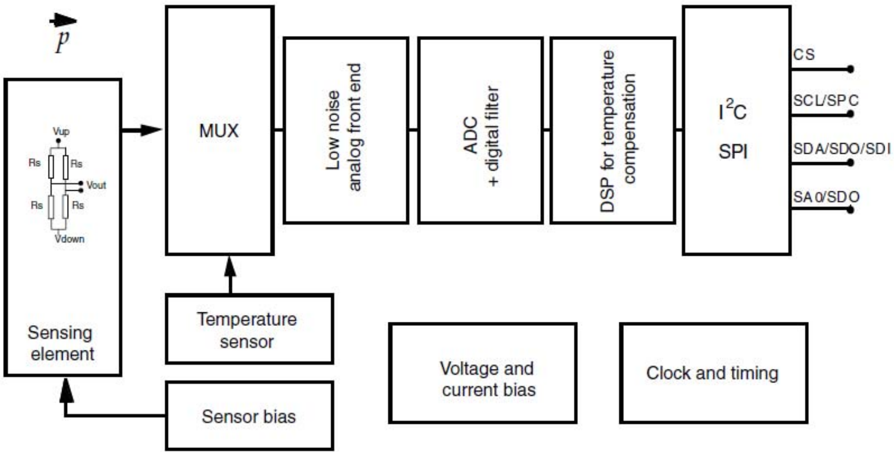

Fig. 3. Barometric pressure sensor based on ADC.

Following the requirements of smart system integration (miniaturization challenges) for smartphones and tablets applications, some companies start to manufacture so-called 'combo' sensors. Nevertheless on many advantages (smaller die, lower parasitic connections power saving, intelligent functions, etc.), which brings such sensor solutions to mobile devices applications, many digital combo sensors as usually are based on the traditional ADC with a limited resolution, complex sensor fusion algorithms and technological limitations from smart system integration point of view. It is still a bottleneck for the next generation of combo sensors, which must include much more additional sensors in one package or in one chip.

2.4. New Advanced Design Approach

The first 10 years of 21st century smartphones became “smarter”, got more powerful processors and operating systems. As it was written in [15], "following the massive proliferation of sensors in smartphones, many have predicted that mobile devices would soon see new generations of smart sensors". Over the last few years, while sensors in smartphones and tablets have gotten smaller, now consume less power, and feature better performance, they haven't gotten much intelligence; while the performance of individual sensors has increased, their functionality has not expanded [15]. The motivation for using smart sensors lies in reducing the power consumption. A smart sensor could also choose to optimize its performance for a specific set of contexts or a segment of use cases [15]. Developers are encouraged to make applications that utilize the data from multiple sensors. But there are key limitations of existing smart, intelligent sensors and sensor systems for smartphones and tablets [16]:

- Level of complexity to implement more different sensors in the same device;
- Design of software adapting to each new sensor (interface, data sampling rate, etc.).

In order to eliminate these both: technological and design limitations the authors have developed a novel integrated circuit - Universal Sensors and Transducers Interface (USTI-MOB), which lets to build easily various sensors and DAQ systems [17]. The IC is based on three novel patented methods for accurate and quick frequency-time measurements. The USTI-MOB can work practically with any quasi-digital sensors, available on the modern sensor market, and especially designed for smartphone, tablets and IoT applications. In addition, the USTI-MOB can be used with resistance, capacitance and resistive bridge sensing elements. If the barometric pressure sensor (Fig. 3) would be design based on the USTI-MOB IC, it will eliminate the complex mixed design and analog components such as ADC, analog front end, filter, etc. (see Fig.4).

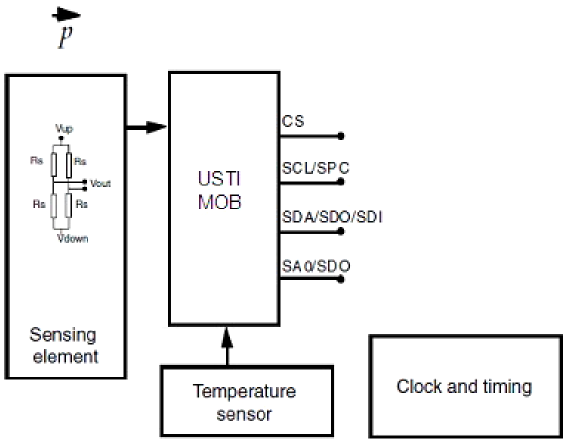

Fig. 4. Barometric pressure sensor based on USTI-MOB IC.

The USTI-MOB can be also connected directly to an application processor or to a sensor hub microcontroller, for example, ML610Q792 (*Lapis Semiconductor*). The multisensor system for smartphones and tablets based on the USTI-MOB IC and various quasi-digital sensors is shown in Fig. 5.

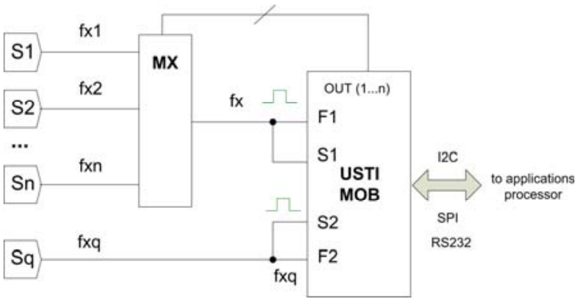

Fig. 5. Multisensor system for mobile devices and IoT with quasi-digital sensors.

The system also contains a digital multiplexer (MX) controlled by the USTI-MOB IC. The MX's output is connected to the first USTI's channel. The second channel can be used for a direct sensor connection.

In case of analog sensors, an intermediate voltage-to-frequency conversion should be used with the help of integrated voltage-to-frequency converter [10]. A sensor system for analog output sensors is shown in Fig. 6. In both cases time-division, space-division and combining channeling can be used [18].

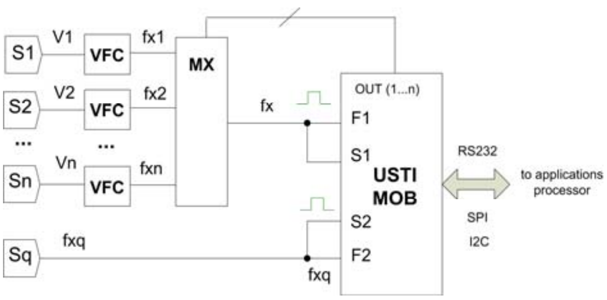

Fig. 6. Multisensor system for mobile devices and IoT with analog sensors

Taking into account that many quasi-digital sensors, integrated voltage-to-frequency converters, digital multiplexers and IC USTI-MOB are manufactured in standard CMOS processes it opens a wide horizon for the future high level system integration According to *InvenSense*, the hierarchy for mobile sensor integration contains three levels dependent on involved hardware [19]: individual sensors; sensor hub and application processor. Due to advanced technologies, which where used at the USTI-MOB design, this component can be used on all these three levels of integration. On the lowest level of individual sensors, the IC can be used for three different sensors: two quasi-digital and one parametric sensing element (resistive, capacitive or resistive bridge). On the 2nd level of integration the USTI-MOB IC can aggregate a lot of sensors output via a digital multiplexer, and on the 3rd level of integration the USTI-MOB can be embedded into an application processor as a firmware IP.

The CMOS digital IC USTI-MOB also compatible with the SoC design approach, when sensors, hub and USTI-MOB itself can be integrated into a single product.

2.5. Calculation and Experimental Results

The prototype of evaluation board (EVAL USTI-MOB) for experimental investigation is shown in Fig. 7.

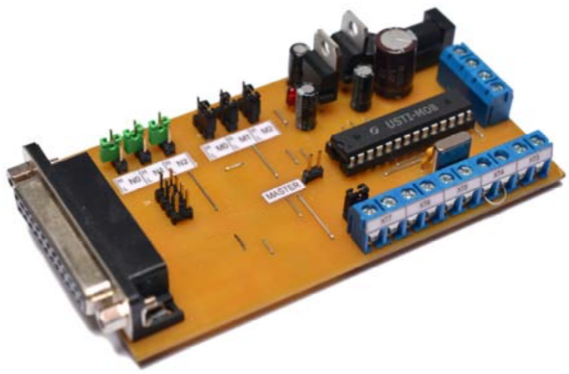

Fig. 7. Prototype of evaluation board EVAL USTI-MOB.

The USTI-MOB has the same measurement modes as the early developed IC USTI [8], but different metrological performance and electrical characteristics (see Table 1), due to the specific application in mobile devices (reduced clock frequency, supply voltage and power consumption).

Table. 1. Maim technical performance of USTI and USTI-MOB IC.

Performance	IC	
	USTI	USTI-MOB
Frequency range of measurement, Hz	0.05 ... 7.5×10^6	0.25 ... 1.9×10^6
Programmable relative error, %	± (1 ... 0.0005)	± (1 ... 0.0005)
Clock frequency, MHz	20	4
Supply voltage, V	5.0	1.8
Current consumption (active mode), mA	11	0.35
Operation temperature range, ^{0}C	- 40 ... + 85	- 40 ... + 85
Overall dimensions for MLF 28-pad package, mm	5×5×1	4×4×1

The IC has a non redundant conversion time, which is dependent on the programmable relative error, and in the worst case can be calculated according to the following equation:

$$t_{conv} = \frac{100}{\delta_x \times f_0} + T_x, \qquad (1)$$

where δ_x is the relative error in %; f_0 = 4 MHz is the reference frequency and $T_x = 1/f_x$ is the period of unknown frequency f_x. The dependence of t_{conv} on the programmable relative error is shown in Fig. 8. In the low and infra-low frequency range, the conversion time t_{conv} is determinated by the period T_x of converted frequency. In order to calculate a measurement time for the USTI-MOB it is necessary to take into account also a communication and calculation times [8].

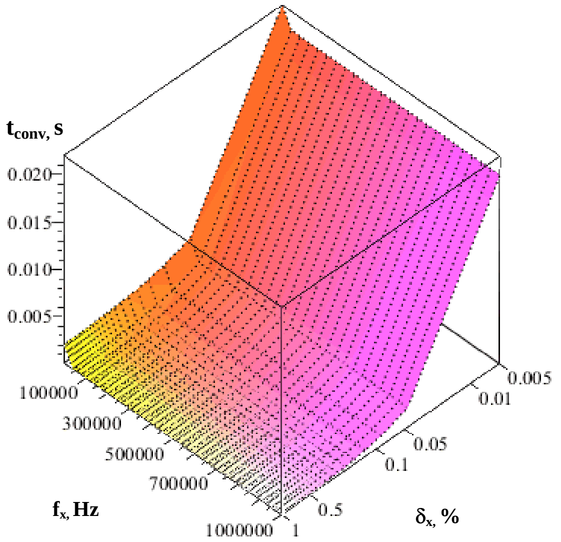

Fig.8. Dependence of t_{conv} (δ_x, f_x) in the frequency range from 500 Hz to 1 MHz.

The USTI-MOB also has one generating mode (for calibration purposes) and 26 measuring modes to measure: frequency, period, its ratio and difference, duty-cycle, duty-off factor, time interval between start- and stop- pulses, pulse width, pulse space, phase shift, frequency deviation (absolute and relative), rotational speed and pulse number. It has also three popular serial communication interfaces and buses: RS232, SPI and I2C.

The USTI-MOB IC in 5 × 5 mm MLF package is shown in Fig. 9.

Fig. 9. USTI-MOB IC in 5 × 5 mm MLF package.

The USTI-MOB IC in available PDIP, TQFP and MLF packages are shown in Fig. 10.

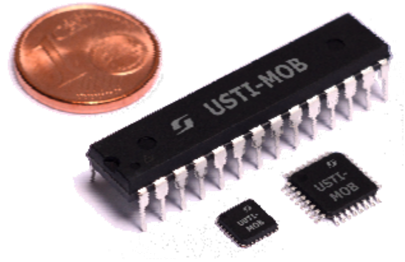

Fig. 10. USTI-MOB IC in PDIP, TQFP and MLF packages.

3. Sensor System Design Example

Let's consider a multisensor system example - a smartphone based weather station (Fig. 11). It contains tree sensors: a quasi-digital, duty-cycle output temperature sensor SMT160-30 from *Smartec* (The Netherlands) in small-size HEMP or SOIC-8 housing [20]; a frequency output module for humidity measurements, and barometric pressure, bridge-type, miniature SMD sensor MS54XX [21]. All of these sensors can be connected directly to one USTI-MOB IC at the same time without any multiplexers.

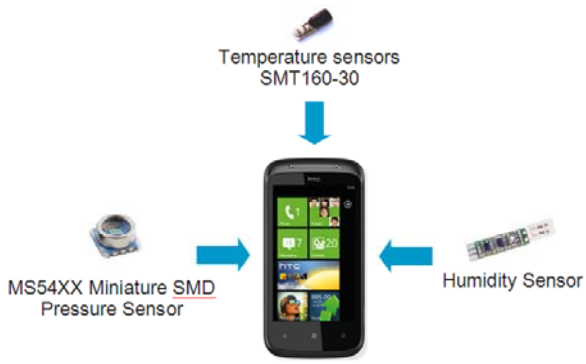

Fig. 11. Smartphone based weather station.

Commands for USTI-MOB working in I2C communication mode are shown in Fig. 12. The format of result of measurement in BCD is shown in Fig. 13. The binary format also possible. In this case instead of <07> command the <08> command must be used [22].

The humidity module is connected to the first IC's cannel, and temperature sensor - to the second channel. Resistance passive bridge measurements are described in details in [8, 22, 23].

The programmable relative error of USTI-MOB for frequency measurements (humidity) must be selected in one order less (or at least in 5 times less), than the sensor error in order to be neglected [8, 24]. So, frequency output humidity sensing modules have 2-3 % error [25], therefore the programmable relative error for the USTI-MOB should be 0.25 %. The digital multiplexer does not introduce any error.

<06><00>; Frequency measurement in the 1st channel (humidity)
<02><02>; Set up the conversion error 0.25 %
<09>; Start a measurement
<03>; Check result status: ‘0’ if ready or not ‘0' if busy
<07>; Get result in BCD format

<06><14>; Duty-cycle measurement in the 2nd channel (temperature)
<09>; Start a measurement
<03>; Check result status: ‘0’ if ready or not ‘0' if busy
<07>; Get result in BCD format

<06><12> ;Resistance-bridge B_x measurement mode (pressure)
<10><13>; Set the charging time 20 ms
<09>; Start measurement
<03>; Check result status: ‘0’ if ready or not ‘0' if busy
<07>; Read conversion result

Fig. 12. Commands for USTI-MOB (I2C slave communication mode).

<Sign><I5><I4><I3><I2><I1><I0><F0><F1><F2><F3><F4><F5>

<Sign> - sign of result: 0x20 (space char) for positive result;
0x2D (minus char) for negative result;
<In> - byte n of integer part of result
<Fn> - byte n of fractional part of result

Fig. 13. BCD format for result of measurement

The duty-cycle is measured by the IC with a maxim possible accuracy, which is determined by time interval measurement error, and it is not necessary to set up the programmable relative error for this measuring mode.

The resistive bridge measurement requires only two external components: capacitor and resistor R=220 Ohm. The considerations about calculation for capacitor value and time constant (commands <10>) are described in details in [8, 22, 23].

4. Conclusions

In order to implement more different sensors in smartphones and tablets easily and overcome existing technological and design limitations due to the complex analog and mixed design, developers should use the alternative, advanced design approach based on precision frequency-to-digital conversion for both: sensor systems and digital sensors for mobile devices. This will drastically increase the number of sensors, which can be embedded into modern smartphones and tablets. As a result, the number of software applications for such devices will be increased in geometrical progression.

The extension of sensors "intelligent" capabilities including a self-adaptation will be available. The process of miniaturization and smart system integration based on the novel design approach boost the creation of multichannel, multifunction (multiparameter) one-chip smart sensors and combo sensors arrays.

Advantages of the proposed design approach are the following:

- Optimized, process compatible architecture for the future smart system integration;
- Much more sensors can be connected to smartphones and tablets;
- Much better metrological performances of various sensors and DAQ systems;
- Wide functionalities, including such new intelligent function as the self-adaptation;
- Simplified sensor fusion algorithms;
- Reduction of the data communication with the main applications processor in mobile devices;
- It meets the IoT device requirements: sensing modality, form factor (size), sensor lifetime, and connectivity;
- Reduced implementation cost and time-to-market.

Any IoT system needs to be able to support quasi-digital (frequency, period, duty-cycle, PWM, etc. output) sensors to be truly flexible. While a solution based on ADC is functionally acceptable, the cost in terms of PCB real estate, system integration level and bill of materials (BOM) can be prohibitive. That’s especially true for IoT systems that must be very small, particularly for wearable (textiles, etc.) and healthcare-related (intra-body or swallowable pills) devices. The integration of the USTI-MOB with high performance has the potential to greatly simplify the design of the system and contribute to further increasing of system level integration, flexibility and functionality. The same is true for mobile devices such as smartphones and tablets.

The core component of novel design approach - new USTI-MOB IC will be available on the modern market in 2015 from the *Technology Assistance BCNA 2010, S .L. (Excelera)*, Barcelona, Spain (http://www.excelera.io).

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