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NOVEL UNIVERSAL FREQUENCY-TO-DIGITAL CONVERTER AND SENSORS INTERFACE INTEGRATED CIRCUITS

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Abstract

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The Universal Frequency-to-Digital Converter (UFDC) and Universal Sensors and Transducers Interface (USTI) integrated circuits (ICs) for different frequency output sensors and transducers were described in the article. All chips are based on four novel patented methods for frequency (period), duty-cycle (duty-off factor), frequencies (periods) ratio and phase-shift measurement. They have a high accuracy, non-redundant conversion time, scalable resolution, programmable relative error, broad frequency range and extended functionality. The ICs have intelligent capabilities including self-identification; self-adaptation and can contain the IEEE 1451.4 TEDS in its flash memory. Such ICs will simplify significantly a digital sensors and smart sensor systems design process, reduce development time, time to market and production price of different applications based on innovative chips while improving sensor performances.

Keywords: quasi-digital sensors, sensors and transducers interface, frequency-to-digital converter, smart sensors, IEEE 1451, TEDS

Анотація

НОВІ ІНТЕГРАЛЬНІ МІКРОСХЕМИ УНІВЕРСАЛЬНИХ ПЕРЕТВОРЮВАЧІВ ЧАСТОТА-КОД І СЕНСОРНИХ ІНТЕРФЕЙСІВ

С. Ю. Юриш

У статті описане сімейство інтегральних універсальних перетворювачів частота-код і мікросхем універсальних сенсорних інтерфейсів, призначених для різноманітних сенсорів і перетворювачів з частотними виходами. Всі ІМС базуються на чотирьох нових запатентованих методах вимірювання частоти (періоду), коефіцієнта заповнення (шпаруватості), відношення двох частот (періодів) і фазового зсуву. Мікросхеми мають високу точність, безнадлишковий час перетворення, масштабовану роздільну здатність, програмовану відносну похибку перетворення й широкий діапазоном перетворених частот та функціональними властивостями. ІМС мають також інтелектуальні властивості, що включають самоідентифікацію й самоадаптацію, а також можливість зберігання у флеш-пам'яті таблиці електронної специфікації TEDS (Transducer Electronic Data Sheet) у відповідності зі стандартом IEEE 1451.4. Такі ІС суттєво спростять розробку (і скоротять її час) цифрових і інтелектуальних сенсорів і систем, зменшать собівартість різних сенсорних систем при поліпшенні їх метрологічних характеристик.

Ключові слова: квазіцифрові сенсори, інтерфейс, перетворювач частота-код, інтелектуальні сенсори, IEEE 1451, TEDS

Аннотация

НОВЫЕ ИНТЕГРАЛЬНЫЕ МИКРОСХЕМЫ УНИВЕРСАЛЬНЫХ ПРЕОБРАЗОВАТЕЛЕЙ ЧАСТОТА-КОД И СЕНСОРНЫХ ИНТЕРФЕЙСОВ

С. Ю. Юриш

В статье описано семейство интегральных универсальных преобразователей частота-код и микросхем универсальных сенсорных интерфейсов, предназначенных для различных датчиков и преобразователей с частотными выходами. Все ИМС базируются на четырех новых запатентованных методах измерения частоты (периода), коэффициента заполнения (скважности), отношений двух частот (периодов) и фазового сдвига. Микросхемы обладают высокой точностью, безизбыточным временем преобразования, масштабируемой разрешающей способностью, программируемой относительной погрешностью преобразования, широким диапазоном преобразуемых частот и функциональными возможностями. ИМС обладают также интеллектуальными возможностями, включающими самоидентификацию и самоадаптацию, а также возможностью хранения во флеш-памяти таблицы электронной спецификации TEDS (Transducer Electronic Data Sheet) в соответствии со стандартом IEEE 1451.4. Такие ИМС существенно упрощают разработку (и сокращают ее время) цифровых и интеллектуальных датчиков и систем, уменьшают себестоимость различных сенсорных приложений при улучшении их метрологических характеристик.

Ключевые слова: квазицифровые датчики, интерфейс, преобразователь частота-код, интеллектуальные сенсоры, IEEE 1451, TEDS

Introduction

Many modern manufacturers today produce sensors and transducers with frequency, period, duty-cycle, time interval, frequencies difference, PWM or pulse number output signal for various physical and chemical, electrical or non-electrical quantities [1-2]. Such so-called quasi-digital sensors have a high accuracy (from 0.01 to 0.003 % relative error and better), for example, pressure sensors and transducers from *Paroscientific, Inc.* (USA) and *Pressure Systems* (USA); the temperature sensor SBE 3plus from *Sea Bird Electronics*, *Inc.*, various quartz crystal microbalance and other resonator-based (superficial SAW, bulk acoustic wave, etc.) chemical, bio- and immunobiosensors, etc. [1]. Quasi-digital sensors and transducers are operating in a broad frequency range, from several hundredth parts of Hz up to some MHz, for example, light and color sensors from *TAOS* (USA), *Hamamatsy* (Japan) and *Melexis* (USA) [1]. In order to convert these informative signals into a digital form, a frequency-to-digital converter based on novel conversion methods should be used.

The number of quasi-digital sensors currently available on the market and these various devices have adopted numerous sensing principles, the task of designing appropriate interfacing integrating circuits (ICs) to satisfy them all appears daunting. Despite the presence of many highly versatile sensor interface chips in the market, they remain limited to analog sensor types.

One of the first ICs for frequency-to-digital conversion was designed at the end of 1980s. It was the 48-pin one-chip specialized microprocessor USP-

30 [3]. The USP works in a pipeline mode and can measure frequency, period, time interval, pulse width and count pulse number. The main demerits of this device are its narrow frequency range: from 0.1 Hz to 100 kHz and high power consumption.

For time interval measurements the IC's ALU uses standard counting method for frequency measurements and indirect counting method for time interval measurements [4]. The absolute accuracy is $\Delta T = \pm 33$ ns at the reference frequency $f_0 = 30$ MHz. This IC has high power consumption.

The universal 42-pin CMOS frequency-to-digital converter K512PS11 (USSR) works in two modes: single conversion and multiple conversions. It is based on the indirect counting method with interpolation [5]. This IC has parallel 16-bit output. The maximal converted frequency is 1 MHz.

The universal sensor interface chip (USIC) can measure frequency and pulse width. It has an 80-pin pack (QFP) and a limited high frequency of 4 MHz [6].

The single-chip (FPGA) 84-pin interpolating time counter described in [7] is based on the classical time interpolation technique. It has limited maximal measurable time interval of 43 s, and only a few measuring functions.

An ASIC of single channel frequency-to-digital converter has been designed to handle one input channel [8]. This ASIC is capable of measuring frequencies from 100 Hz to 100 kHz. The frequency measurement relative error is 0.1 %. The chip can be interfaced to a 16-bit bus. The hybrid technique for frequency measurements has been used in order to meet these specifications. Disadvantages of this IC are its low accuracy and narrow converted frequency range.

A frequency-to-digital converter (FDC) from *AutoTEC*, implemented on a Xilinx FPGA provides digital data for frequency signals [9]. The FDC has 16-bit and 12-bit counters and uses a 1 MHz free running clock frequency as a reference. The frequency range is from 35 Hz to 24 kHz, with absolute error $\Delta_x = \pm 5$ Hz and relative full-scale error $\delta_x = 0.2$ %. Disadvantages of this IC are the same: low accuracy and narrow converted frequency range.

Acam-messelectronic GmbH produces four modifications of the Time-to-Digital Converter (TDC) [10]. These CMOS ICs provide frequency, time and phase measurement. The TDC-GP1 is a universal 2-channel time-to-digital converter with a typical resolution of 125 ps and a maximal measuring range of 200 ms. A quartz clock in the range from 500 kHz to 35 MHz is needed for reference. The TDC-GP1 is realized in a 0.8 μm CMOS process and packaged in 44 TQFP. The IC offers a standard 8-bit bus interface.

The TDC-F1 is a complex 8-channel time-to-digital converter with a120 ps resolution for each channel or 4 channels with 60 ps resolution each. The measurement range is from 5 ns to 7.8 μs. Output data are available directly on a 24-bit parallel bus. The reference clock is from 1 MHz to 40 MHz. The chip is packaged in 160-pin PQFP.

The IC TDC-GP2 has resolution of 50 ps. Its measurement range is from 3.5 ns to 1.8 μs. The TDC-GP2 has an SPI compatible serial digital output. The time-to-digital converter TDC-GPX has a resolution of 10 ... 81 ps and measurement range from 10 ns to 10 μs.

All four ICs are using the modified method of delayed coincidences. The main disadvantages of these time-to-digital converters are the following: limited low frequency range; narrow functionality; only slave communication mode; and relatively high price.

The 80/32-pin ICs (System-on-Chip) of sensors signal processor SSP1492/1493 from *Sensor Platforms* (USA) include a frequency-time mode converter with scalable resolution and conversion time based on classical methods for frequency measurement [11]. They have SPI and I^2C serial communication interfaces. These ICs have narrow functionalities for frequency-time domain signals: only period and pulse width measurements are possible.

All integrated converters and interfacing ICs considered above except the time-to-digital converters from *Acam-messelectronic GmbH* are based on classical conversion methods for frequency-time parameters to digital. Hence, they cannot be used with all existing modern frequency-time domain sensors due to low accuracy in comparison with sensor's accuracy or/and narrow frequency range. Further, they do not cover all frequency–time informative parameters of modern quasi-digital sensors and transducers such as duty-cycle, duty-off factor, phase-shift, frequency (period) ratio and difference, frequency deviation, etc. In order to overcome the mentioned disadvantages of existing integrated frequency-to-digital converters the family of integrated Universal Frequency-to-Digital Converter (UFDC) and Universal Sensors and Transducers Interface (USTI) ICs with significantly improved metrological performance, extended frequency range and functionality were designed and developed. Both types of ICs are Application Specific Integrated Processors (ASIP) that should be programmed once by a manufacturer. The ICs design was implemented by using embedded programming rather that the custom IC development.

Universal Frequency-to-Digital Converters

The universal frequency-to-digital converter (UFDC) family of ICs contains the UFDC-1, UFDC-1M-16, UFDC-2 and UFDC-2M-20 integrated circuits. All these ICs are based on four novel patented conversion methods for frequency (period), its ratio, duty-cycle and phase-shift; and have a scalable resolution, non-redundant conversion time and programmable relative error of measurement, which is constant in all frequency range. The UFDC-1 and UFDC-1M-16 have 16 measuring and one generate (8 MHz rectangular pulses) modes. The UFDC-2 and UFDC-2M-20 have 26 measuring and one generate (10 MHz rectangular pulses) modes. The UFDC-1 evaluation board is shown in Figure 1.

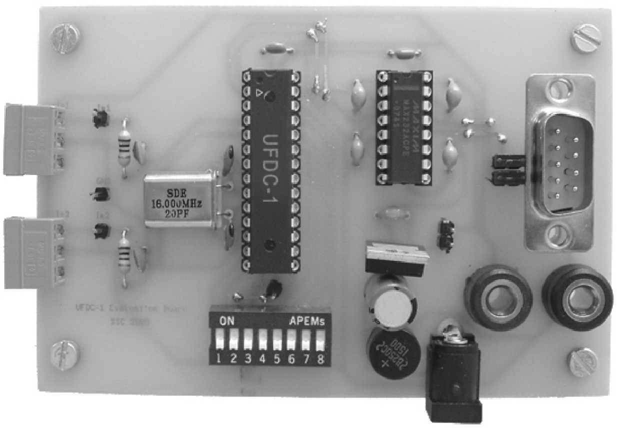


Fig. 1. The UFDC-1 evaluation board

The modified method of the dependent count is used for frequency (period)-to-digital conversion [12]. Like to the early proposed method of the dependent count [13] it lets convert frequency f_x, which exceeds the reference frequency f_0: ($f_x >> f_0$). But in comparison with the original method of the dependent count, the initial stage for determination which of frequency is greater ($f_x <> f_0$) is not necessary, as well as it is not necessary to change the equations for further frequency or period calculation.

In comparison with the UFDC-1 [14] the high speed version UFDC-1M-16 [15] has internal reference frequency f_0 = 16 MHz and reduced conversion time at the same programmable relative errors.

In comparison with the developed earlier integrated universal frequency-to-digital converters the UFDC-1 and UFDC-1M-16, the UFDC-2 and UFDC-2M-20 have extended high frequency range, increased functionality (due to addition absolute and relative frequency deviation measuring modes), improved quartz-accurate automated calibration procedure, increased accuracy and shorter conversion time t_{conv} (decreased in 32 times for the UFDC-2M-20). All ICs have RS-232 (422/485) master and slave communication modes, SPI (slave communication mode), and I^2C interfaces (slave communication mode).

The UFDC-2 can keep an IEEE 1451's Transducer Electronic Data Sheet (TEDS) in its flash memory with the aim to simplify the sensors and transducers configuration in a system and ability of self-identification and self-adaptation. The last feature includes a possibility for flexible trade off accuracy for speed and vice versa during each measurement.

Together with appropriate transducers' parameters, the TEDS for frequency output sensors must also contain the value of quantization error for frequency-to-digital conversion. This parameter can be changed during measurements depending on application and adaptive measuring algorithm.

The UFDC-2 IC covers three main functions of smart transducers: high accuracy frequency (time)-to-digital conversion, TEDS storage in the flash memory and communications. Because of such ICs, the design and development of IEEE 1451 compatible sensors and transducers will be quick, low-cost and effective.

Universal Sensors and Transducers Interface

The universal sensors and transducers interface (USTI) is designed for operation in a wide frequency range from 0.05 Hz to 9 MHz (144 MHz with prescaling) with programmable accuracy δ_x from 1 % to 0.0005 %, scalable resolution and appropriate non-redundant conversion time t_{conv} from 5 μs to 0.01 s. The relative quantization error δ_q does not dependent on the converted frequency. It is constant in the whole frequency range (from f_{xmin} to f_{xmax}) and less than the programmable relative error $\delta_q < \delta_x$. The IC supports an advanced quartz-accurate automated calibration procedure; the RS-232 (422/485) serial interface with programmable communication speed up to 38400 baud rate (for slave mode), 3-wire SPI and 2-wire I²C interfaces; master and slave communication modes. There are one 10 MHz generate mode (for a calibration purpose) and 29 measuring modes designed for conversion to digital of any frequency-time parameters of sensor's and transducer's output: frequency, period, duty-cycle, duty-off factor, frequency and period ratios and differences, time interval, pulse space and width, phase shift, absolute and relative frequency deviation, pulse number count and rotation speed.

It addition, the USTI can directly convert to digital a resistance, capacitance and resistive bridge parameters of different sensing elements. In this case the number of external components is minimal. The conversion methods for these parameters are based on modified direct interfacing methods for sensing elements described in [16, 17].

Intelligent (smart) USTI's features include a self-adaptation possibility (an opportunity to trade off accuracy for speed and vice versa during each measurement) and a possibility to keep in the USTI's flash memory the IEEE 1451 TEDS with the aim to simplify sensors configuration in a system, ability of self-identification and self-adaptation.

The USTI as well as the rest members of integrated converters family promise to reduce significantly a digital sensors and smart sensor systems development time, while improving sensor performances. Due to communication features and two physically separated channels the USTI can be used in various multi-sensor systems. A signal processing includes everything needed for accurate measurement of the frequency-time domain sensor signals as well as for communication with a PC or master microcontroller. An important feature of USTI is also that it is flexible and easy to use.

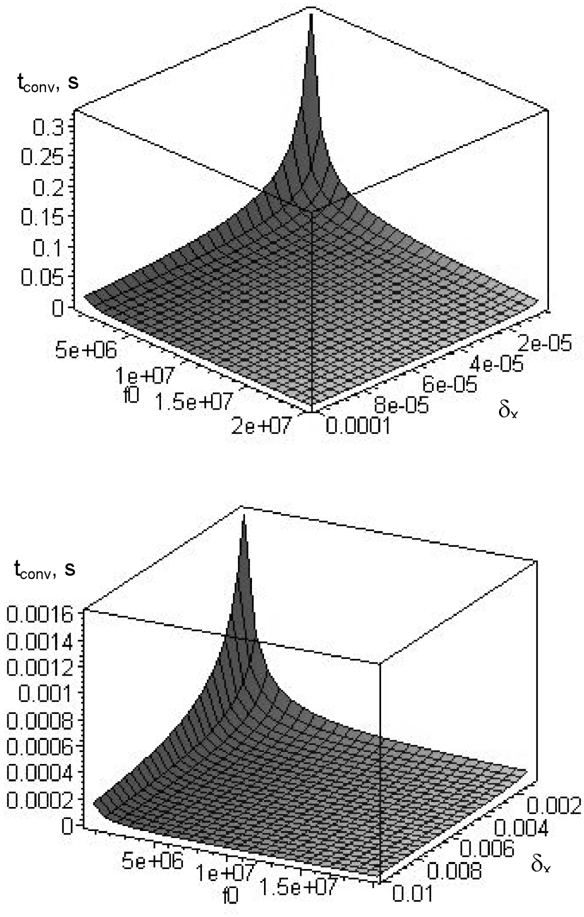
One of main USTI's parameter is the conversion time. According to the modified method of the dependent this time is non-redundant, adaptive (determined only by the programmable relative error δ_x) and minimum possible. The conversion time can be calculated according to the following equation:

$$\begin{cases} t_{conv} = \dfrac{1}{f_x}, & if \quad \dfrac{N_\delta}{f_0} \prec T_x \\ t_{conv} = \dfrac{N_\delta}{f_0} + (0 \div T_x), & if \quad \dfrac{N_\delta}{f_0} \geq T_x \end{cases}, \qquad (1)$$

where f_0 is the reference frequency; $N_\delta = 1/\delta_x$ is the number proportional to the programmable relative error δ_x; $T_x = 1/f_x$ is the period of unknown frequency. Simulation results of conversion time for the USTI prototype chip are shown in Fig. 2. The conversion time is most significant at precision low and infralow frequency-to-digital conversions but does not exceed the period T_x in this frequency range. The internal reference frequency is f_0=625 kHz for USTI and 20 MHz for the modified high-speed chip version USTI-1M-20.

A conversion rate T_{meas} for the USTI includes three components: conversion (t_{conv}), communication (t_{comm}) and calculations (t_{calc}) times:

$$T_{meas} = t_{conv} + t_{comm} + t_{calc} \qquad (2)$$



a)

b)

Fig. 2. Modeling results for dependence of $t_{conv} = \varphi\,(f_0, \delta_x)$ at range of variables f_0=625 kHz ...20 MHz, δ_x = 0.001...0.000005 (a), and δ_x = 0.01...0.001 (b)

In turn, the communication time for slave communication mode (RS-232 interface) can be calculated according to the following equation:

$$t_{comm} = 10 \cdot n \cdot t_{bit}, \qquad (3)$$

where t_{bit} = 1/300, 1/600, 1/1200, 1/2400, 1/4800, 1/9600, 1/14400, 1/19200, 1/28800 or 1/38400 is the time for one bit transmission; n is the number of bytes (n=13-24 for ASCII format). As usual, the right choice of the baud rate (maximum possible for a certain application) is $t_{comm} \le t_{conv.}$ For example, the communication time at 38 400 baud rate will be t_{comm} = (0.0034 ... 0.00625) s.

The communication speed for SPI and I^2C interfaces is 100 kHz. The calculation time t_{calc} depends on operands and approximately equals to 4.5 ms.

Let's compare the conversion time of the USTI that is based on the modified method of the dependent count with conversion times, which can be achieved by using any classical or other advanced conversion methods described in [2]. For the indirect counting method with the reference frequency f_0=20 MHz, the relative error δ_x = 0.0005 % and conversion time that does not exceed one period T_x the frequency range will be essentially limited to 0.05...100 Hz. In case of direct counting technique, for the same relative error and gate time 0.01 s it will be possible to convert only frequencies from the range $f_x \in$ [~ 44.7 kHz ... 20 MHz] and for all relative error except the δ_x = 0.0005 %, the conversion time will be redundant. For advanced conversion methods, for example, reciprocal, ratiometric, M/T, constant elapse time, single- and double buffered, DMA [2], at the reference frequency f_0=20 MHz and gate time T_0=0.01 s the conversion time also will be redundant for all relative error except the δ_x = 0.0005 %. In other words, the conversion time will be the same — 0.01 s for the relative error 0.0005 % and relative error 1 %.

Experimental Results

The objective of experimental investigations was to determine major metrological performances of designed ICs and their limits. The measurement set up for the UFDC-2 is shown in Figure 3.

Two TTL-level square waveform pulse signals whose frequency-time parameters must be measured, were fed from two function generators Agilent 33220A to inputs FX_1 and FX_2 (the 1st and 2nd channel) of the UFDC-2 evaluation board. The UFDC-2 was programmed to measure frequency with the minimal possible relative error 0.0005 %. The supply voltage of the evaluation board was +5V dc, provided by the Promax FAC-363B power supply. The frequencies generated by the generators were in the range from 0.04 Hz up to 9 MHz. It was measured by a frequency counter Agilent 53132A with ultra high oven stability internal time base. The two-channel digital oscilloscope Promax OD-571 monitored the signals waveforms as well as pulse rise and fall tail times. Before measurements, the UFDC-2 was calibrated in the working temperature range: +23.5 ... + 25.4 °C.

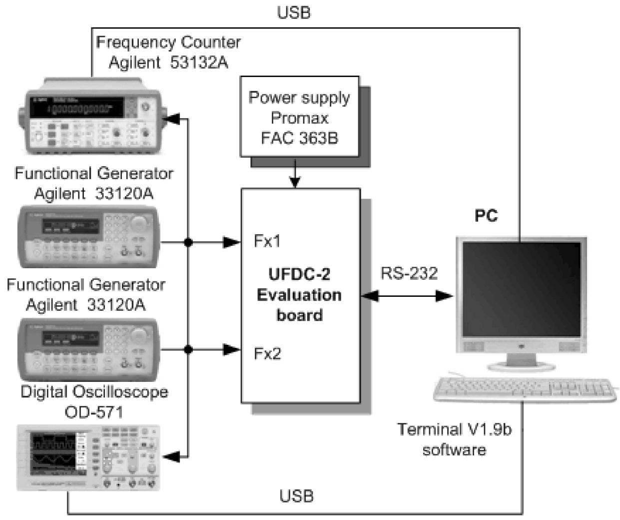


Fig. 3. Measurement set up for determination of metrological performances

The measured values were sent to a PC via an RS-232 interface implemented with the ST202D IC. The user interface was realized with the help of terminal software *Terminal V1.9b* for Windows XP. Every measurement consisted of 60 values. The measurement errors were evaluated from appropriate statistics. The results for a 9 MHz, 1 MHz and 100 kHz square waveform pulse signal are shown in Figure 4 (a-c). The statistical characteristics are presented in Table 1. As it is visible from the table, the maximal relative error does not exceed the programmable δ_x < 0.0005 % in all frequency range including low and infralow frequencies.

The maximal possible frequency of a square waveform pulse signal for the UFDC-2, USTI and its high speed modifications was 9.1 MHz without prescaling; the minimal possible frequency was 0.04 Hz.

During the experiments, the minimal possible pulse width (t_p), pulse space (t_s) and time interval (t_x) were also determined. The minimal possible value for these time parameters was 1.5 μs.

Another important parameter for a square waveform pulse signal is the duty-cycle. The duty-cycle values determined for the maximal frequency ranges are adduced in Table 2.

Comparative performances for series of the UFDC and USTI ICs of frequency-to-digital converters are shown in Table 3. The USTI series ICs have identical 2 channels for all measuring parameters excluding resistive, capacitance and resistive bridges while the UFDC series of ICs can measure only frequency and period in the second channel.

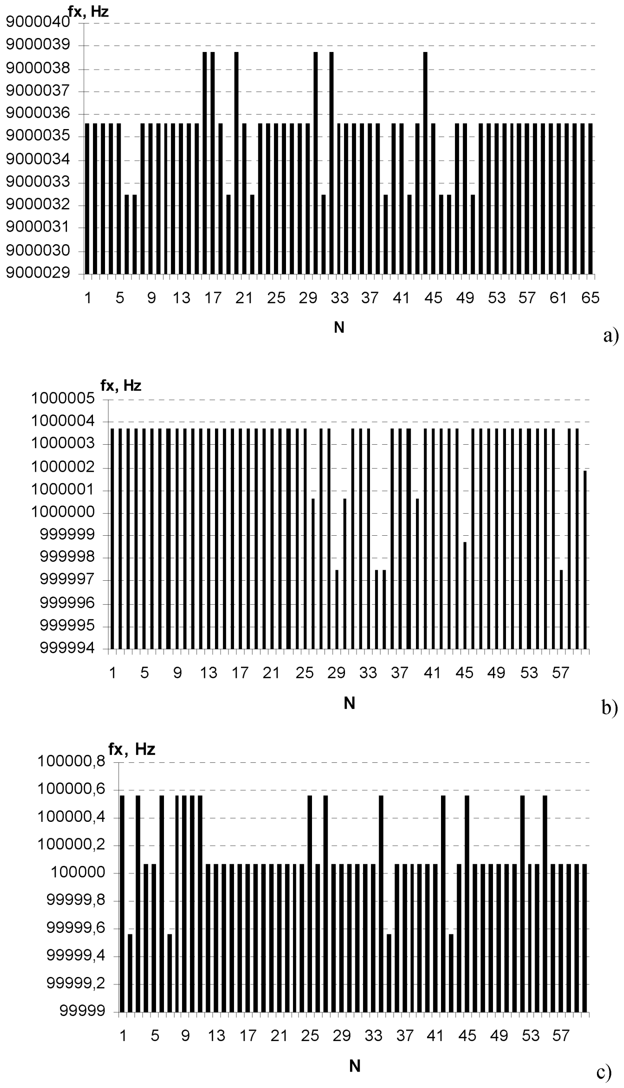


Fig. 4. Measured results for square waveform signal with frequency 9 MHz (a), 1 MHz (b) and 100 kHz (c)

Applications and Examples

The applications of designed ICs are numerous: any frequency-time domain sensor including digital, multiparameters, multifunctional, smart sensors and systems (due to the programmable accuracy and adaptive, non-redundant conversion time); high-end, mid- and low-range Anti-lock Braking System (ABS); desktop and handheld multifunctional frequency counters for industrial measurements; multimeters for frequency-time parameters of signals; tachometers and tachometric systems; data acquisition systems and boards for frequency-time parameters, virtual instruments, communication applications, measuring systems for analytical chemistry, electronic noses and tongues, etc.

ICs will simplify significantly a digital sensors and smart sensor systems design process, reduce development time, time to market and production price of different applications based on innovative chips while improving sensor performances. In comparison with the direct microcontroller interfacing of different quasi-digital sensors and sensing elements these ICs also let to eliminate many design problems caused by the use of advanced measurement methods for frequency measurements, microcontroller choice, its programming and additional error components due to so-called program-dependent or software-related effects [16]. It also allows a move from a traditional analog sensor output to quasi-digital. No output standardization is necessary as in case of analog sensors.

Combining silicon micromachining designs and processes with the advanced universal sensors and transducers interfacing circuits will overcome many of the early limitations for single-chip sensors. By eliminating the need for ADC, the frequency (period, duty-cycle or PWM)-to-digital conversion schemes reduce the systems complexity. The results are high-performance single-chip sensors with truly digital output (RS-232 interface) or bus output (SPI or I^2C).

These chips can be embedded into any existing frequency-time domain output sensors or transducers (with the help of integrated, SoC or hybrid technologies) to produce IEEE 1451.4 compatible sensors as well as into IEEE 1451.4 compatible data acquisition systems. Due to all these, smart transducers manufactures will secure additional 15...20 % of global sensors market, which were not available before the IEEE 1451 standardization. Design and development of IEEE 1451 compatible sensors and transducers will be quick, low-cost and effective. Such approach will improve the level of commercial adaptation of IEEE 1451 standards family in industry.

Together with all IEEE 1451 standards family benefits (including self-identification, simple installation, upgrade and maintenance) customers will receive the self-adaptation capability and digital plug-and-play sensors, using all advantages of frequency-time parameters as informative parameters of sensors' outputs: high noise immunity and output signal power; high accuracy of frequency standards (reference frequency and time base); wide dynamic range, simple long distance transmitting, simplicity of communication, interfacing, integration and coding., etc.

Table 1

Statistical Characteristics of the Experimental Results

Parameter	**Value**		
	9 MHz	1 MHz	100 kHz
Number of measurements, N	65	60	60
Minimum f_x (min), Hz	9000032.48	999997.488	99999.5635
Maximum f_x (max), Hz	9000038.73	1000003.74	100000.563
Sampling Range, f_x (max)- f_x (min), Hz	6.2515	6.2515	1
Median	0	0	0
Arithmetic Mean, Hz	9000035.42	1000003.05	100000.146
Variance	2.405	3.1488	0.0692
Standard Deviation	1.5508	1.7745	0.2631
Coefficient of Variation	5803428.66	563543.777	380129.039
Confidence Interval at probability $P = 97$ %	f_x ϵ [9000035 ... 9000035.83]	f_x ϵ [1000002.55 ...1000003.54]	f_x ϵ [100000.073 ... 100000.22]
Relative error, %	0.00039 < 0.00050	0.00030 < 0.00050	0.00014 < 0.00050

Table 2

Limit Duty-Cycle for the Input Signal Depending on the Maximal Frequency.

Duty-cycle, %	**Frequency f_x, MHz**
47.5 ... 57.0	9
42.0 ... 62.0	8
36.5 ... 66.0	7
32.0 ... 71.5	6
26.0 ... 76.5	5
20.5 ... 80.0	4
any	< 3

Examples of USTI applications for a wide frequency range light-to-frequency converter photo IC S9705 (*Hamamatsu Photonics K.K.*, *Japan*) and multiparameter sensor system, which contains a monolithic quartz resonator high accurate pressure transducer of Quartzonix™ Series 960 (*Pressure Systems, USA*) and semiconductor temperature sensor SMT160-30 with duty-cycle output (*Smartec, The Netherlands*) are shown in Figure 5 a, b respectively.

The S9705 is a light sensor that combines a photodiode and current-to-frequency converter on a CMOS chip and outputs an oscillating frequency (duty ratio 50 %) proportional to input light intensity [18]. The S9705 has a wide dynamic frequency range from 0.1 Hz up to 1 MHz and can be easily measured with constant relative error in the broad frequency range, non-redundant conversion time and scalable resolution when used with the USTI or UFDC ICs. The programmable relative error for USTI or UFDC ICs must be chosen 0.25 % in order to be neglected in comparison with the sensor's error. Other light and color sensors with a wide frequency range, for example, TSL230, TSL235, TSL237, TSL238, TSL TSL245 and TCL203 (*TAOS, USA*) or light-to-frequency converter MLX75304 (*Melexis Microelectronic Systems, Belgium*) [19] can be interfaced with the USTI or UFDC by the same manner. Such approach can be used for creation low-cost, high performances sensors systems for different applications, for example, small distance measuring system, color classification system, light parameters monitoring and control; fluid absorption measurement; paper handling, oximeters, etc.

The pressure sensor series 960 [20] in multiparameter sensor system (Fig.5 b) is connected to the 1st channel of USTI. Taking into account a high sensor's accuracy (0.01 % FS relative error), the USTI's relative error for frequency-to-digital conversion should be chosen 0.001 % in order to be neglected in comparison with the pressure sensor's error. The temperature sensor SMT160-30 [21] with duty-cycle output is connected to the 2nd channel. It is not necessary to choose the relative error for duty-cycle measurement because of it is measured by the USTI with the maximum possible accuracy.

Instead of SMT160-30 temperature sensor, the second output from the 960 pressure sensor can be connected to the 2nd channel of USTI. The frequency on this output is proportional to temperature.

Conclusions

The developed ICs significantly increase accuracy and functionality, extend frequency range and decrease the cost and time-to-market for different sensor systems and digital sensors based on frequency-to-digital conversion, which can be done now by UFDC and/or USTI integrated converter and interfacing circuits. Such ICs can work practically with any frequency, period, duty-cycle, time interval, PWM, phase-shift, pulse number output sensors and transducers in a broad frequency range from part of Hz to some MHz with constant relative error 0.0005 % and non-redundant conversion time.

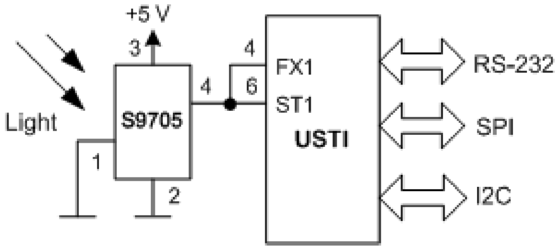
Table 3

Comparative performances of USTI and UFDC series of ICs

Parameters \ **IC**	UFDC-1	UFDC-1M-16	UFDC-2	UFDC-2M-20	**USTI**	**USTI-1M-20**
Programmable relative error, %	1 ... 0.001	1 ... 0.001	1 ... 0.0005	1 ... 0.0005	1 ... 0.0005	1 ... 0.0005
Minimal frequency, Hz	0.05	1	0.05	1	0.05	1
Maximal frequency, MHz	7.5 (120)*	7.5 (120)*	9 (144)*	9 (144)*	9 (144)*	9 (144)*
Internal reference frequency, MHz	0.5	16	0.625	20	0.625	20
Conversion time, s	0.0002 ... 0.2	0.00000625 ... 0.00625	0.00016 ... 0.32	0.000005 ... 0.01	0.00016 ... 0.32	0.000005 ... 0.01
Frequency generator mode, MHz	8	8	10	10	10	10
Number of channels	2 different	2 different	2 identical	2 identical	2 identical	2 identical
Number of measuring modes	16	16	26	26	29	29
TEDS Support	-	-	●	●	●	●
Frequency	●	●	●	●	●	●
Period	●	●	●	●	●	●
Phase shift	●	●	●	●	●	●
Time interval	●	●	●	●	●	●
Duty-cycle	●	●	●	●	●	●
Duty-off factor	●	●	●	●	●	●
Frequency/ period difference	●	●	●	●	●	●
Frequency/ period ratio	●	●	●	●	●	●
Rotation speed	●	●	●	●	●	●
Pulse width	●	●	●	●	●	●
Space interval	●	●	●	●	●	●
Pulse number (events) counting	●	●	●	●	●	●
Frequency deviation relative/ absolute	-	-	●	●	●	●
Resistive	-	-	-		●	●
Capacitance	-	-	-		●	●
Resistive bridge	-	-	-		●	●

(*) — with prescaling

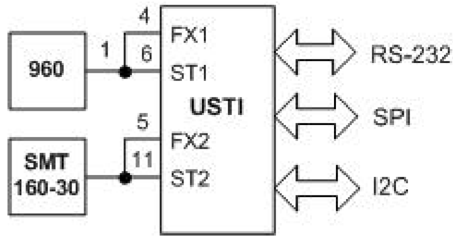
Experimental results confirm high metrological performance for prototypes of novel smart universal integrated frequency-to-digital converters and interfacing circuits for quasi-digital sensors and transducers. Its conversion time is non-redundant, adaptive and minimum possible. The relative error of USTI, UFDC-2 and its high speed chip versions USTI-1M-20 and UFDC-2M-20 in the whole frequency range including low and infralow frequencies was below 0.00043 % (in the worst case). This was less than the programmable relative error (0.0005 %). Due to scalable resolution, programmable relative error and non-redundant conversion time the chips can work with any existing frequency-time domain sensor to produce a digital output or create multiparametric smart sensors and systems.



Commands for RS-232 (slave mode):

>A02 ;0.25 % relative error
>M00 ;Frequency measurement in the 1st channel
>S ;Start measurement
>R ;Read result
1000277.75 – result of measurement (Hz)

a)



Commands for RS-232 (slave mode):

>A09 ;0.001 % relative error
>M00 ;Frequency measurement in the 1st channel
>S ;Start measurement
>R ;Read result
40 000.04 – result of measurement for pressure (Hz)
>M04 ;Duty-cycle measurement in the 2nd channel
>S ;Start measurement
>R ;Read result
0.4328 – result of measurement for temperature

b)

Fig.5. USTI application examples: (a) — light sensor system based on S9750 light-to-frequency converter; (b) — multiparameter sensors system based on Series 960 pressure sensor and temperature sensor SMT160-30 (b)

Such ICs will simplify significantly a digital sensors and smart sensor systems design process, reduce development time and production price of different applications based on innovative chip while improving sensor performances. In comparison with the direct microcontroller interfacing the designed ICs also let to eliminate many design problems connected with the use of advanced conversion methods for frequency-time parameters, embedded microcontroller choice, its programming and additional error components due to so-called program-dependent or software-related effects.

In addition the USTI and UFDC (UFDC-2 and UFDC-2M-20) series of ICs can store the TEDS in its flash memory. The described chips can be embedded into any existing frequency-time domain output sensors or transducers (with the help of integrated or hybrid technologies) to produce IEEE 1451.4 compatible sensors as well as into IEEE 1451.4 compatible data acquisition systems.

Smart transducers manufactures will receive a unique opportunity to produce low-cost IEEE 1451 compatible sensors with minimum possible hardware. They should not think now about the frequency-to-digital conversion accuracy. Only one component can cover three main functions of smart transducers: frequency (time)-to-digital conversion with high metrological performances, TEDS storage in the flash memory and communications.

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