Smart and Intelligent Optoelectronic Sensor Systems: OEM Design Approach

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***Abstract*—Light-to-frequency converters are widely used in various optoelectronic sensor systems. However, a further frequency-to-digital conversion is a bottleneck in such systems due to a broad frequency range of light-to-frequency converters. This paper describes an effective OEM design approach, which can be used for smart and intelligent sensor systems design. The design is based on novel, multifunctional integrated circuit of Universal Sensors & Transducers Interface especially designed for such sensor applications. Experimental results have confirmed an efficiency of this approach and high metrological performances.**

Keywords-optical sensor; smart sensor system, light-to-frequency converter, USTI, intelligent sensor system, IEEE 1451

I. INTRODUCTION

Optoelectronic sensors are widely used in various applications such as medical, automobile, environmental, bio-chemical, etc. Many of them are based on integrated light-to-frequency converters, which convert a light intensity to quasi-digital (frequency or duty-cycle) format for direct connection to a microcontroller, DSP or interfacing with a PC. In comparison with analog output (voltage or current), the frequency signal as an informative parameter of sensor's output has a lot of advantages, namely: a high noise immunity, high reference accuracy, wide dynamic range, multiparametricity, simplicity of coding, multiplexing, interfacing and integration, etc.

Modern light-to-frequency converters [1] have a broad frequency range: from part of Hz to 1.6 MHz (Table 1). Nevertheless a simple frequency-to-digital conversion (based on classical methods for frequency measurements) can be performed by any low-cost microcontroller, a wide dynamic frequency range of such converters brings as usually, many design problems. In order to get reasonable or high metrological performances of designed optical sensor systems, the frequency-to-digital conversion should be based on advanced methods for frequency measurements. Such methods must have a constant quantization relative error in a whole broad frequency range, scalable resolution, non-redundant conversion time and a possibility to measure frequency, which exceeds a reference frequency: $f_x > f_0$ in order to design a sensor systems with a reasonable power consumption.

Existing on the modern sensor market digital light sensors with embedded ADCs as usually have a slow conversion time, for example, the embedded 16-bit ADC of light sensor from Intersil (ISL29015) has the integration time 45-90 ms [2]; the ADC from Maxim MAX9635 has the conversion time 97-107 ms [3]. Such sensors can be used for proximity or ambient light applications, but it can not be used for light sensing applications, in which a conversion speed is a critical parameter.

TABLE I. LIGHT-TO-FREQUENCY CONVERTERS' PERFORMANCES

Sensor (LFC)	Performances		
	Output Frequency Range	***Spectral Response, nm***	***Non-linear FS Error, %***
TAOS (USA)			
TSL230	0.4 Hz … 1.1 MHz	350…1000	0.2
TSL235	0.4 Hz … 500 kHz	350…1000	0.2
TSL237	2 Hz … 600 kHz	350…1000	1
TSL245	0.4 Hz … 500 kHz	850…1000	0.2
Hamamatsu (Japan)			
S9705	0 Hz … 1 MHz	300…1000	3
Melexis (Belgium)			
MLX75304	1 Hz … 1.6 MHz	500…1000	N/a

N/a – not available.

The main aim of these research and development was to propose a universal design solution for all existing light-to-frequency converters in order to eliminate all mentioned above design problems, and introduce intelligent and smart features for various sensor systems, which can be realized in different technologies: hybrid, standard CMOS technology, System-on-Chip (SoC) or/and System-in-Package (SiP).

This paper is divided into four main parts. The first part describes a design approach for various optical sensor systems based on a light-to-frequency converter (LFC) and Universal Sensors and Transducers Interface circuit (USTI). The description includes the system design in term of OEM hardware and software. The second part devotes to experimental investigation of designed optoelectronic sensor system prototype based on the light-to-frequency converter S9705 from Hamamatsu [4]. The third part includes an experimental determination of main metrological performances of designed sensor system. The last part of the paper provides conclusions and future research directions.

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II. Smart Sensor System Design

A. Universal Sensors and Transducers Interface

The proposed solution is based on the developed by the author USTI integrated circuit. In comparison with the developed earlier and introduced on the modern market in 2004 and 2007 Series of Universal Frequency-to-Digital Converters UFDC-1 and UFDC-1M-16 respectively [5, 6] this new IC has extended frequency range up to 9 MHz without prescaling and 144 MHz with prescaling, reduced relative error up to ±0.0005 %, increased functionality and decreased conversion time. It is based on the patented modified method of the dependent count for quick and precision measurement of frequency and period of electrical signals [7]. This 2-channel IC has three popular serial interfaces: RS232, I^2C and SPI, which are widely used in various sensor systems. It contains of three main blocks: measuring unit, communication unit and time-to-digital converter (TDC). Only one external component – a 20 MHz quartz crystal oscillator should be used as a reference. The measuring unit releases 2-channel measurements of various frequency-time parameters of electrical signals with programmable relative error form 1 % to 0.0005 %: frequency, period, duty-cycle, phase shift, time intervals, duty-off factor, pulse number, frequency (period) deviation, frequencies or periods ratios and differences, etc. The communication unit supports three popular serial interfaces, such as RS232 (master and slave communication modes with programmable baud rate), SPI and I^2C (slave communication mode). The TDC is used in parameter-to-digital converter for a direct interfacing of capacitive, resistive and bridge sensing elements to USTI.

The USTI can work in RS232 master communication mode. In this mode, neither microcontroller nor PC or DAQ system are necessary to control this IC. It will continuously generate measuring results on its output.

B. Sensing Element

The S9705 is a CMOS photo IC combining a current-to-frequency converter and photodiode and outputs an oscillating frequency (duty ratio 50 %) proportional to input light intensity incident in the photodiode [4].

The CMOS level digital output allows direct connection to the USTI. The sensing element has a wide dynamic range, spectral response (see Table 1), and light intensity can be easy measured by the USTI. The light-to-frequency converter S9705 and USTI are shown in Figure 1, and circuit diagram of optoelectronic sensor system example based on these components is shown in Figure 2.

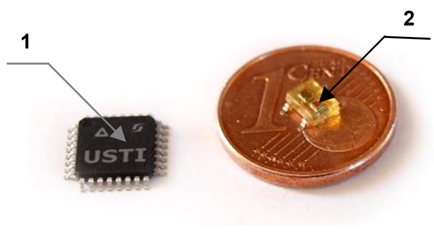

Figure 1. USTI (1), and light-to-digital converter S9705 (2).

Other optical sensors, for example, colour sensor TCS230 from TAOS (USA) [1] or reflective colour sensor OPB780 from OPTEK Technology [8] can also be interfaced by the same manner. Two frequency output sensors can be connected to the USTI at the same time.

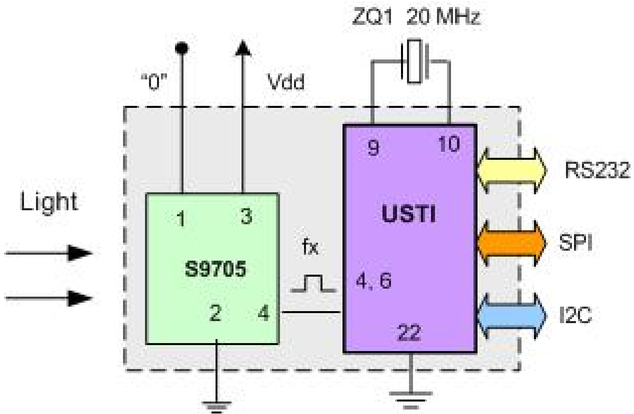

Figure 2. Circuit diagram of optoelectronic sensor system.

A software example for the RS232 interfacing slave connection mode for two optical sensors (light sensor S9705 and colour sensor OPB780) is shown in Figure 3.

```
>A02    ;Set the relative error 0.25 %
>M00    ;Set up a frequency measurement mode in the 1st channel
>S      ;Start a frequency measurement (light sensor)
>C      ;Check the measurement status ('r'-ready, 'b' -in progress
>R      ;Read a result of frequency measurement in Hz
>462987.345

>M0E    ;Set  up a frequency measurement mode in the 2nd channel
>S      ;Start a frequency measurement (colour sensor)
>C      ;Check the measurement status ('r' -ready, 'b'-in progress
>R      ;Read a result of frequency measurement in Hz
>37005.0119
```

Figure 3. Commands for RS232 communication mode at light and colour measurements by the USTI.

The command 'A02' sets the relative error for frequency-to-digital conversion [9] and should be use only once. The relative error must be in ten times less (or at the least, in 5 times less) than the sensor's error in order to be neglected. Appropriate command 'M' sets the frequency measurement mode in the 1st and 2nd channels. The command 'S' starts measurement in appropriate channel. The command 'C' checks the measurements status and returns the value 'b' if the measurement in progress or the value 'r' if the measuring results is ready. The last command 'R' reads results. The use of 'C' command is very important at low frequencies measurements. In opposite side, there is a risk to get a previous result instead of the new one.

Any terminal software can be used with the USTI in RS232 slave communication mode (for example, Terminal V1.9b Window [10]). The following options should be selected for this software: appropriate number of serial port, baud rate – 2400; data bits – 8; Parity – none; Stop Bits – 1; Handshaking- none. For data acquisition, the LabView software or similar can be easily used.

C. Conversion Time

The conversion rate of USTI is determined by the method of frequency measurement [7] and can be calculated according the following equation:

$$\begin{cases} t_{conv} = \dfrac{1}{f_x} \quad if \quad \dfrac{N_\delta}{625\ kHz} \prec T_x \\ t_{conv} = \dfrac{N_\delta}{625\ kHz} + (0 \div T_x) \quad if \quad \dfrac{N_\delta}{625\ kHz} \geq T_x \end{cases}, \tag{1}$$

where $N_\delta = 1/\delta$ is the number proportional to the required programmable relative error δ; $T_x = 1/f_x$ is the period of converted frequency, f_0=625 kHz is the internal reference frequency of USTI.

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

$$T_{meas} = t_{conv} + t_{comm} + t_{calc} \tag{2}$$

All these components can be calculated by the same way as was described in [6]. For example, the communication time for a slave communication mode (RS232 interface) can be calculated according to the following equation:

$$t_{comm} = 10 \cdot n \cdot t_{bit}, \tag{3}$$

where t_{bit} is the time for one bit transmitting; n is the number of bytes (n=13…24 for ASCII format).

The communication time for SPI interface should be calculated as:

$$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCLK}}, \tag{4}$$

where f_{SCLK} is the serial clock frequency, which should be chosen for the USTI in the range from 100 to 500 kHz; n=12…13 is the number of bytes. The number n is dependent on measurement result format: BCD (n=13) or binary (n=12). The communication standard mode's speed for the I^2C interface can be determined according to the same equation (4), where instead of f_{SCLK} the serial clock frequency f_{SC} should be used, which equals to 100 kHz for the USTI; n=12…13 is the number of bytes for measurement result: BCD (n=13) or binary (n=12).

The calculation time depends on operands and is as usually t_{calc} ~ 3.6 ms.

Due to non-redundant conversion time for the modified method of the dependent count [7] it is possible to obtain the conversion time, less than in digital output optical sensors mentioned above. The same is also true for the design approach, when analog light sensor (with voltage output), voltage-to-frequency converter and USTI are used to build a sensor system. The conversion time can be decreased in 3-10 times in comparison with existing standard integrated digital sensors, mentioned above [2, 3].

D. Intelligent Features

One of the intelligent functions of modern sensor system is so-called self-identification. The USTI can contain a Transducer Electronic Data Sheet (TEDS) according to the IEEE 1451 standard in its memory. A possible TEDS for optical sensor system is shown in Table 2. This TEDS must also contain a value of programmable relative error for the frequency-to-digital conversion (USTI relative error).

TABLE II. TEDS FOR OPTICAL FREQUENCY OUTPUT SENSOR

TEDS Structure	Example of Light-to-Frequency Converters	
Basic TEDS	Manufacturer ID	19
	Model ID	9705
	Version letter	S
	Serial number	00639F
Standard and Extended TEDS (fields will vary according to transducer type)	Calibration date	21 September 2010
	Spectral Response	300-1000 nm
	Frequency output minimal	0.1 Hz
	Frequency output maximal	1 MHz
	Linearity	±3 %
	USTI's relative error	±0.25 %
User Area	Sensor location	A18-2
	Calibration due date	21 September 2011

The USTI supports three functions of smart transducers: high accurate frequency (time)-to-digital conversion, TEDS storage in the flash memory and communications.

III. EXPERIMENTAL RESULTS

The aim of experimental investigation was to determine main metrological performances of the designed optical sensor system based on the light-to-frequency converter S9705 (Hamamatsu, Japan) and USTI IC. The measuring set-up is shown in Figure 4.

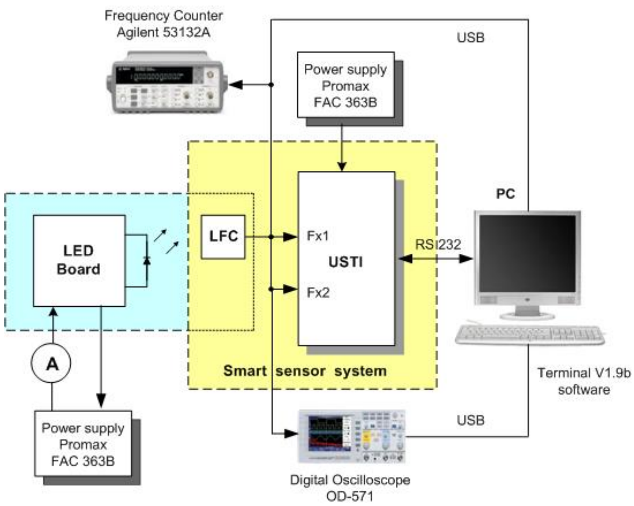

Figure 4. Measuring set-up.

Preliminarily, the USTI has been calibrated at laboratory temperature range (+25.3 ^{0}C to +26.4 ^{0}C) in order to eliminate additional systematic error due to quartz oscillator trimming inaccuracy (calibration tolerance) and a short term temperature instability [11]. The USTI has been connected to a PC, where terminal software Terminal v1.9b was running.

The light-to-frequency converter S9705 has mounted on a LED evaluation board together with a white light diode, the light intensity of which was set-up with the help of current source (Promax FAC 363B) and changing by a potentiometer with 25 μA step. The current through this diode was measuring by an amperemeter (Figure 4).

The circuit diagram and photo of the LED evaluation board are shown in Figures 5 and 6 respectively.

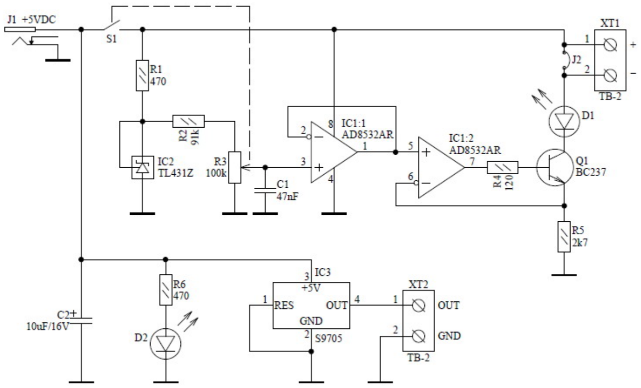

Figure 5. Circuit diagram of LED evaluation board.

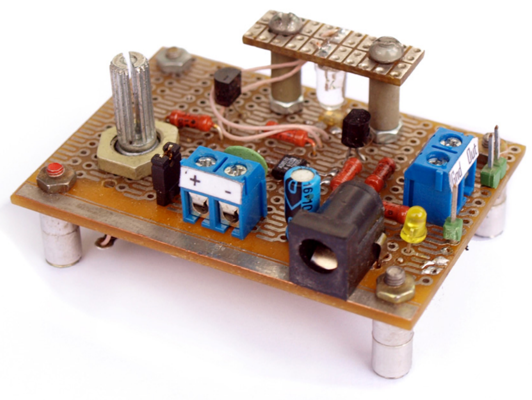

Figure 6. LED evaluation board.

The output of LFC was directly connected to the USCI. The frequency counter Agilent 53132A was used for frequency measurements in parallel with the USTI, and digital oscilloscope - for wave form visualization at LFC's output/USTI input. The frequency measurements have made for minimal and maximal possible frequencies of LED evaluation board: 5 Hz and 462 kHz respectively for both cases: without and with Schmidt trigger (74HC14D). Oscillograms of investigated sensor's output signals are shown in Figures 7-12.

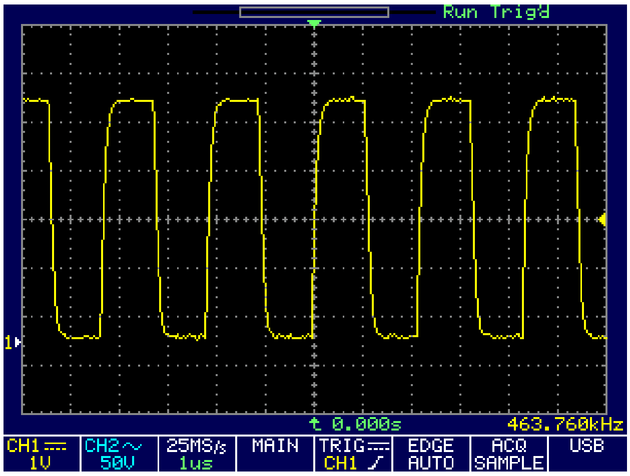

Figure 7. Oscillograms of maximal frequency signal (~ 463 Hz).

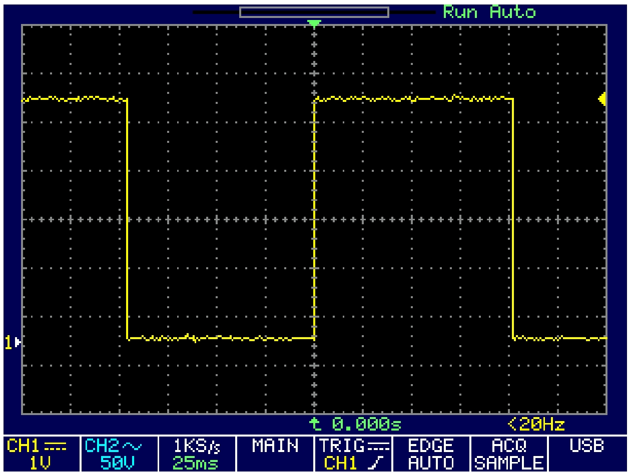

Figure 8. Oscillograms of minimal frequency signal (~ 5 Hz).

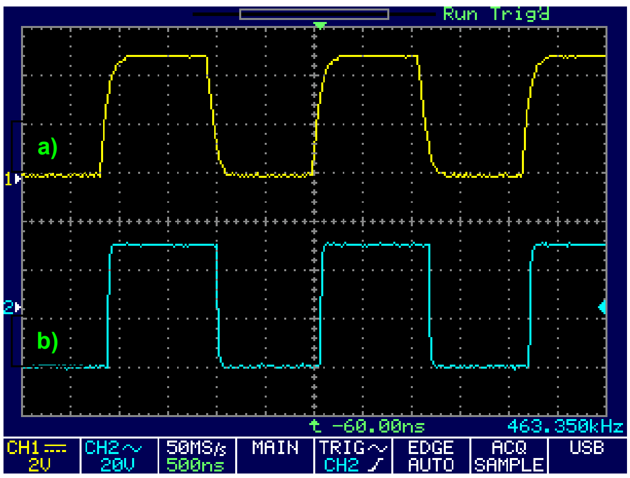

Figure 9. Oscillograms at USTI input for frequency signal ~463 Hz: without Schmidt trigger (a) and with Schmidt trigger (b).

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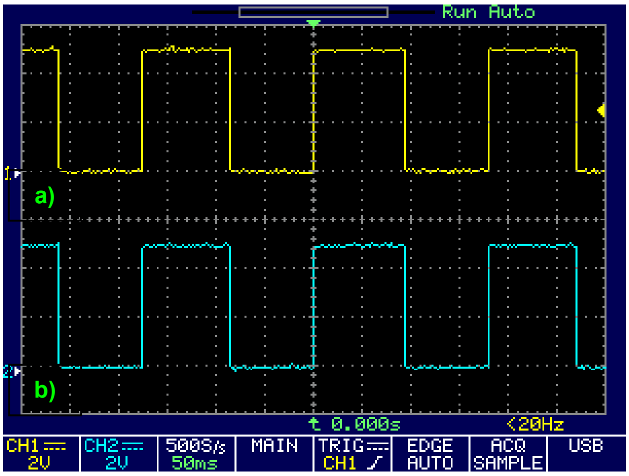

Figure 10. Oscillograms at USTI input for frequency signal ~5 Hz: without Schmidt trigger (a) and with Schmidt trigger (b).

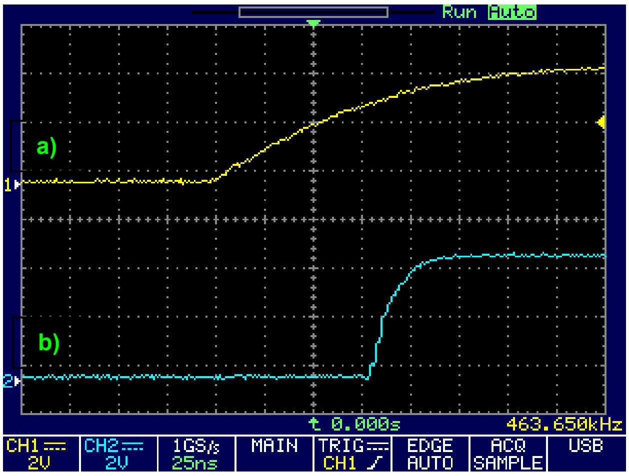

Figure 11. Front of 463 Hz input pulse signal: without Schmidt trigger, rise time 110 ns (a) and with Schmidt trigger, rise time 24 ns (b).

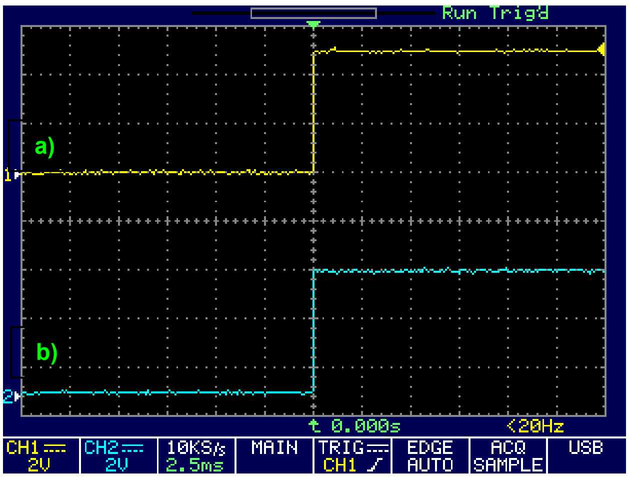

Figure 12. Front of 5 Hz input pulse signal: without Schmidt trigger, rise time 80 μs (a), and with Schmidt trigger, rise time 70.7 μs (b).

The dependence of LFC's output frequency on current through the white light diode on the LED evaluation board is shown in Figure 13.

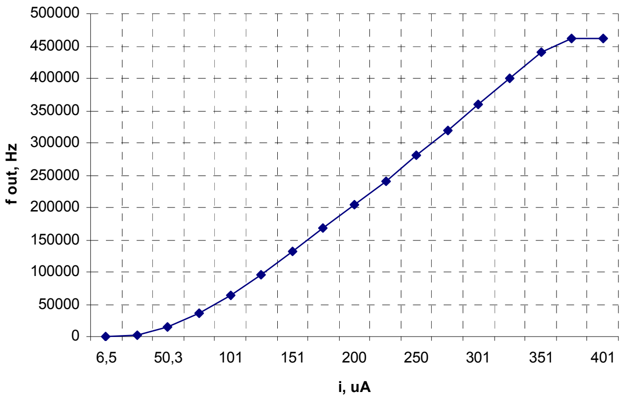

Figure 13. Output frequency vs. current through a white light diode.

Each of investigated frequencies where measured 60 times and classical statistics was used for results processing. Measuring results for maximal and minimal frequencies for both: without and with Schmidt trigger are shown in Figure 14 and 15.

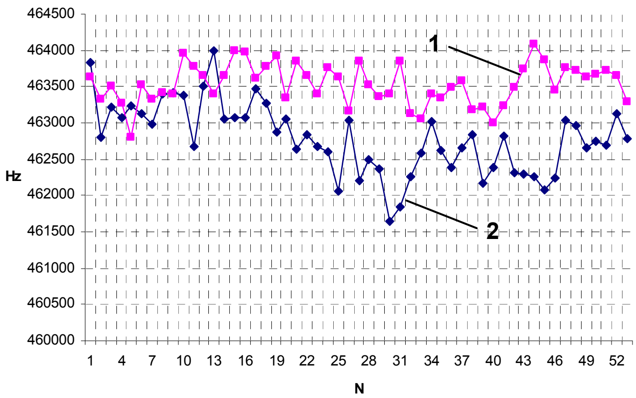

Figure 14. Measuring results for maximal frequency ~ 463 Hz: with Schmidt trigger (1), without Schmidt trigger (2).

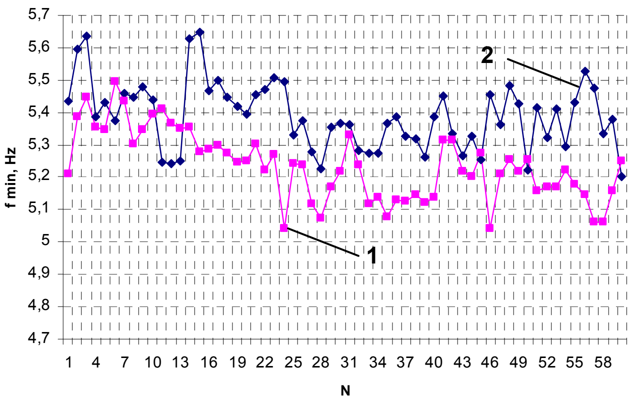

Figure 15. Measuring results for minimal frequency ~ 5 Hz: with Schmidt trigger (1) and without Schmidt trigger (2).

The χ^2 test for goodness of fit test was applied to investigate the significance of the differences between observed data in the histograms and the theoretical frequency distribution for data from the Gaussian distribution law.

The number of equidistant classes was calculated according to the following equation:

$$k = 1.9 \times N^{0.4}, \quad (5)$$

where N is the number of measurements.

At probability P = 97 %, and 6 equidistant classes k=6, the hypothesis of Gaussian distribution law can be accepted for all sets of measurement data. The statistical characteristics are adduced in Table 3 and 4.

TABLE III. STATISTICAL CHARACTERISTICS (AT 463 KHZ FREQUENCY MEASUREMENT)

Parameter	**463 kHz**	
	Without Schmidt trigger	**With Schmidt trigger**
Number of measurements, *N*	53	60
Minimum f_x (min)	461653.265	464151.555
Maximum f_x (max)	463991.336	0.0062
Sampling Range, f_x (max) - f_x (min)	2338.0705	1354.2603
Arithmetic Mean	462788.685	463572.681
Variance	234229.738	6.6E-0009
Standard Deviation	483.9729	283.4972
Coefficient of Variation	956.2286	1635.1932
Confidence interval for arithmetic mean at *P*=97 %	462644.42< f_x < 462932.95	463493.257 < f_x < 463652.105
Relative error, %	0.014	0.16
χ^2 – test (S) at: k=6; P = 97 % χ^2_{max} = 8.9	1.7272	2.5423
Hypothesis about Gaussian distribution	Accepted	Accepted

As it is shown from the tables, the Schmidt trigger does not increased accuracy of frequency-to-digital conversion.

IV. CONCLUSIONS

The proposed design approach for optoelectronic sensor systems based on the USTI IC gives a unique opportunity to create various OEM sensor systems with high metrological performances including intelligent feature such as self-identification. Taking into account, that many semiconductor sensors and the USTI IC are made according to CMOS standard technological processes, different sensor systems and digital sensors can be realized in various existing technologies: hybrid, system-in-chip and system-in-package.

Since 2011 the USTI is available on the modern market from Technology Assistance BCNA 2010 S. L., Spain [12].

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TABLE IV. STATISTICAL CHARACTERISTICS (AT 5 HZ FREQUENCY MEASUREMENT)

Parameter	**5 Hz**	
	Without Schmidt trigger	**With Schmidt trigger**
Number of measurements, *N*	60	60
Minimum f_x (min)	5.2014	5.041
Maximum f_x (max)	5.6466	5.4959
Sampling Range, f_x (max) - f_x (min)	0.4452	0.454
Arithmetic Mean	5.3899	5.236
Variance	0.0109	0.1071
Standard Deviation	0.1045	0.0001
Coefficient of Variation	51.577	48.907
Confidence interval for arithmetic mean at *P*=97 %	5.3606 < f_x < 5.4192	5.206 < f_x < 5.266
Relative error, %	0.54	0.57
χ^2 – test (S) at: k=6; P = 97 % χ^2_{max} = 8.9	6.6726	1.8498
Hypothesis about Gaussian distribution	Accepted	Accepted

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