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A Simple and Universal Resistive-Bridge Sensors Interface

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Abstract: Resistive-bridge sensors are widely used in various sensor systems. There are many sensor signal conditioners from different manufacturers for such sensing elements. However, no one existing on the modern market integrated converter for resistive bridge sensors can work with both: resistive-bridge sensing elements and resistive-to-frequency and -duty-cycle converters' outputs. A proposed and described in the article universal interface for resistive-bridge sensing elements and bridge-output-to-frequency and/or duty cycle converters based on the designed Universal Sensors and Transducers Interface (USTI) integrated. It is based on a simple, cost effective three-point measuring technique and does not require any additional active components. The USTI IC is realized in a standard CMOS technology. The active supply current at operating voltage +4.5 V and clock frequency 20 MHz is not more than 9.5 mA This paper reports experimental results with a strain gauges bridge emulator and differential pressure resistive bridge sensor SX30GD2. *Copyright © 2011 IFSA.*

Keywords: Resistive sensor bridges, Universal sensors and transducers interface, Resistive-bridge sensors, Bridge-to-frequency converter, USTI, Sensor signal conditioners.

1. Introduction

A Wheatstone bridge is widely used to convert the resistance variation of sensors and transducers that is related to the physical quantity into a voltage or current. Today many companies produce various resistive-bridge sensors, for example, SX30 Series differential pressure sensors *(Honeywell);* piezoresistive strain gauges; load cells; temperature, force, acceleration, magnetoresistive sensors HMC1052 and AAH002 (*Honeywell*); vacuum, absolute and differential pressure sensors HM, AP301, 3000, 5000, 7000 Series (*Merit Sensor);* Series SW415 barometric pressure sensors (*Sensonor),* Series SPD300 and SPD015 absolute pressure sensors *(Smartec),* etc. All datasheets for sensors mentioned above are available online at manufactures' web sites.

To converter output bridge voltages into digital, analog-to-digital converters are often used, when the resistive sensor bridge is supplied by a voltage or current. The same or another dc reference source is used to perform precise measurement of the bridge-output voltage. Taking into account that the output bridge voltages are small, they must be amplified and filtered before digitization, and a high performance ADC should be used [1, 2]. 18-, 20- and 24-bit precision ADCs for bridge sensors are produced by several manufacturers, for example, ADS1130, ADS1230 and ADS1232/34 from *Texas Instruments* [3-5]. Such classical solution is relatively expensive, because it requires precision components.

A solution with an embedded into a microcontroller ADC is described in [6] and requires analog multiplexer, operation amplifier and at least, six external discreet passive components as resistors and capacitors.

A low cost direct resistive-bridge sensors – to – microcontroller interface and its applications for some sensors and transducers are described in [2, 7, 8]. A microcontroller, external or internal Schmidt trigger and a few passive components are used for direct resistive sensor bridge–to–digital conversion.

However, the microcontroller based resistive-bridge – to – digital conversion needs a careful consideration and reduction additional errors due to a trigger noise, which depends on power supply noise and various program-related effects [9, 10].

ZMDI, Maxim, Texas Instruments, Smartec and others produce today integrated sensor signal conditioners and universal transducers interface (UTI) circuits with digital and quasi-digital outputs respectively for resistive bridge sensors for various industrial applications including automotive and medical. Main performances of some high performances integrated sensor signal conditioners are shown in Table 1.

Table 1. Main Performances of High-Performance Integrated Industrial Sensor Signal Conditioners.

Type	ADC, Resolution, bit	Output	Notices
ZMDI			
ZMD21013	-	SPI	3 channel sensor bridge
ZMD31010	14	ZACwire serial 1-wire	Offset and gain compensation
ZMD31014	14	I^2C and SPI	14-bit resolution
ZMD31015	14	Digital 1-wire	12-bit resolution
ZMD31020	12	I^2C	Piezo-resistive bridge sensor types
ZMD31030	12	PWM, LIN compatible	Sample rate 100 Hz
ZMD31035	12	Digital 1-wire, LIN compatible protocol	Piezo-resistive bridge sensor types
ZMD31050	9 to 15	PWM, I^2C, SPI, ZACwire	Additional analog outputs
ZMD31150	13 to 16	ZACwire and I^2C	Sensor specific correction
Maxim			
MAX1464	16		12-bit digital output and 4-20 mA analog output
Smartec			
UTI03	13 to 14	Period modulated output	Resistive bridges 250 Ω - 10 Ω with maximum imbalance ± 4 % or ± 0.25 %

The Universal Transducer Interface (UTI) is a complete analog front end for low frequency measurement applications, based on a period-modulated oscillator. Sensing elements (resistive bridge) can be directly connected to the UTI without the need for extra electronics. The UTI outputs a microcontroller-compatible period-modulated signal [11].

ZMDI provides mixed-signal integrated circuits for highly accurate amplification and sensor specific correction (offset, temperature drift, nonlinearity) of signals from resistive bridge sensor elements. The relative FS error is 0.1/0.25 %.

MAX1464 form *Maxim* to be tested with a resistive bridge pressure sensor to form a high-precision intelligent pressure monitoring system, the conversion rate 15 times / sec, measurement error is less than ± 0.1 %.

Often, for example, in remote sensing applications, the resistance variation is converted into a frequency [12-17] or duty-cycle signal [14, 16, 17]. An integrated two-wire bridge-to-frequency converter described in [12] is intended to be used as a remote signal conditioner for sensor bridges such as strain-gauge bridges or platinum-wire temperature-sensing bridges. The converter has sensitivity on the order of 1 Hz per 1-μV/V relative bridge output. A center frequency of 10 kHz allows the application of an untrimmed bridge with an unbalance up to ±10 000 μV/V. The instability is less than 10^{-4} per Kelvin and per 1-V supply-voltage variation. The untrimmed transfer inaccuracy is lower than 1 %. The linearity error is lower than 0.01 %. Different bridge readout functions can be chosen by different circuit configurations. The converter can be connected to a single supply voltage. The frequency output is modulated on the supply current. The supply voltage is 12-24 V.

A fully integrated bridge-output-to-frequency converter realized as signal-conditioning circuitry for a one chip smart thermal mask flow sensor has described in [13]. The frequency converter reads out four separate resistor bridges of the air-flow sensor in order to realize high sensitivity and directional flow measurement over the full angle range of 360^0. The converter selects the sensor bridges individually by means of a microprocessor controlled analog multiplexer. The flow velocity and direction are also calculated by the microprocessor. The relative measurement cancels all first-order errors. The center frequency is 10 kHz and the sensitivity - 1 Hz/(μV/V). A bridge-offset of 10 mV/V is allowed, and the linearity error is 0.1 %.

The CMOS bridge to frequency converter with gain and offset control is presented in [15]. This circuit incorporates Wheatstone bridge was balanced, the simulated center frequency varied from 10.9 kHz to 220 kHz by changing the external capacitor from 1.5 nF to 0.05 nF. The maximum deviation in frequency from the central frequency increases from 4.5 kHz to 67 kHz as the capacitor decreases.

V. Ferrary *et al* [16] reported a signal conditioning circuit based on a relaxation oscillator proposed for use with resistive bridge sensors. The circuit provides a rectangular-wave output whose frequency is related to the bridge unbalance, and duty-cycle is a function of overall sensor bridge resistance, hence of the sensor operating temperature. In this way, two measurement values are simultaneously and independently carried on the same output signal.

An application specific integrated circuit (ASIC) front-end interface in 0.7 μm CMOS for resistive-bridge sensors is proposed by V. Ferrary *et al* [17]. The circuit is also based on a relaxation oscillator where the frequency is related to the fractional bridge unbalance, and the duty-cycle depends on the overall bridge resistance, which typically is related to temperature. The circuit has been characterized by means of a 1-kΩ reference bridge showing frequency and duty-cycle sensitivities of 60.4 Hz/(1000 ppm) and 0.276%/(mΩ/Ω), respectively, at a central frequency about 6.4 kHz.

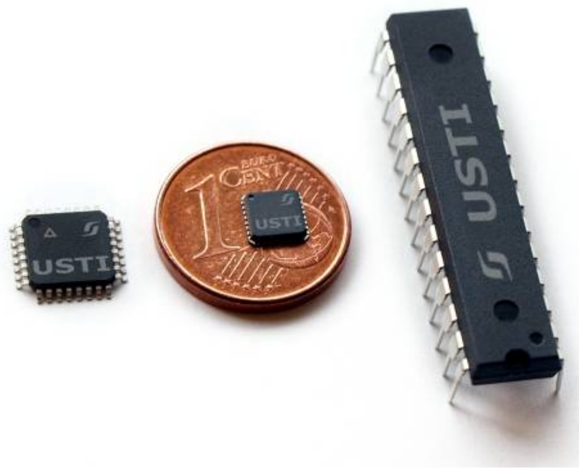
No one existing on the modern market integrated converter for resistive bridge sensors (Table 1) can work with both: resistive-bridge sensing elements and frequency and duty-cycle signal conditioners' outputs, described above.

The universal solution - a universal interfacing circuit for resistive-bridge sensing elements and bridge-output-to-frequency and/or duty cycle converters designed by the author is described in this article, which is an extension version of the conference paper presented at SENSORDEVICES conference [18].

This article is organized as follow. The Section 2 describes briefly the Universal Sensors and Transducers integrated circuit (USTI) and resistive-bridge sensors interface of its basis. It includes a short measuring method description and guide to selection of external components. The Section 3 is devoted to experimental investigations of differential pressure sensor system based on pressure sensor series SX30GD2 from Honeywell and strain gages emulated by the Strain Indicator Calibrator Vishay 1550A.

2. Resistive-Brigde – to – Digital Converter

The designed universal resistive bridge-to-digital converter (Fig.1) is based on the Universal Sensors and Transducers Interfacing (USTI) integrated circuit [19].



(a) (b) (c)

Fig. 1. Universal Sensors and Transducers Interfacing circuit (USTI) in (a) 32-lead Plastic Quad Flat Package (TQFP); (b) miniaturized 32-pad Micro Lead Frame (MLF) 5 mm × 5 mm × 1 mm; and (c) 28-lead Plastic Dual Inline Package (PDIP) packeges.

The Universal Sensors and Transducers Interface (USTI) is a complex fully digital CMOS integrated circuit based on novel patented methods for frequency, period, its ratio, duty-cycle and phase-shift measurements (Fig. 2).

It uses the similar conversion method described in [2, 9], which is based on so-called a three-point measuring technique [20]; but instead of the external or internal Schmidt trigger, an embedded analog comparator has been used. The resistive sensor bridge is considered as a resistor network with three inputs and one output [2]. The resistance of each input to the output depends on the measurand. Using each input to turn to charge/discharge a capacitor connected to the bridge output yields three different time intervals. For a full bridge, the ratio between the difference between two time intervals and the third time interval yields the fractional resistance change [2]. This change x for each bridge arm can be obtained by the following way:

$$x = \frac{t_1 - t_3}{t_2} \quad (1)$$

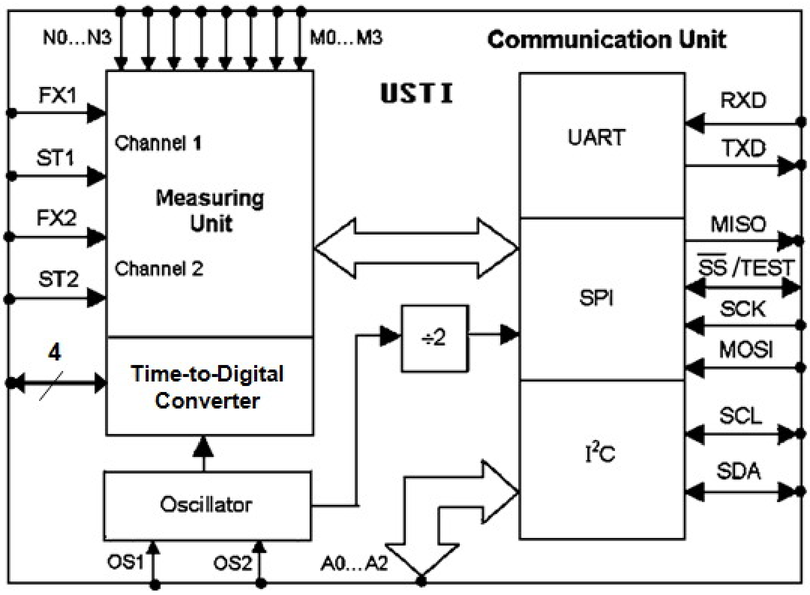


Fig. 2. The USTI Block Diagram.

The direct resistive-bridge sensors interface needs only a few external components such as a limiting resistor R and capacitor C (Fig. 3).

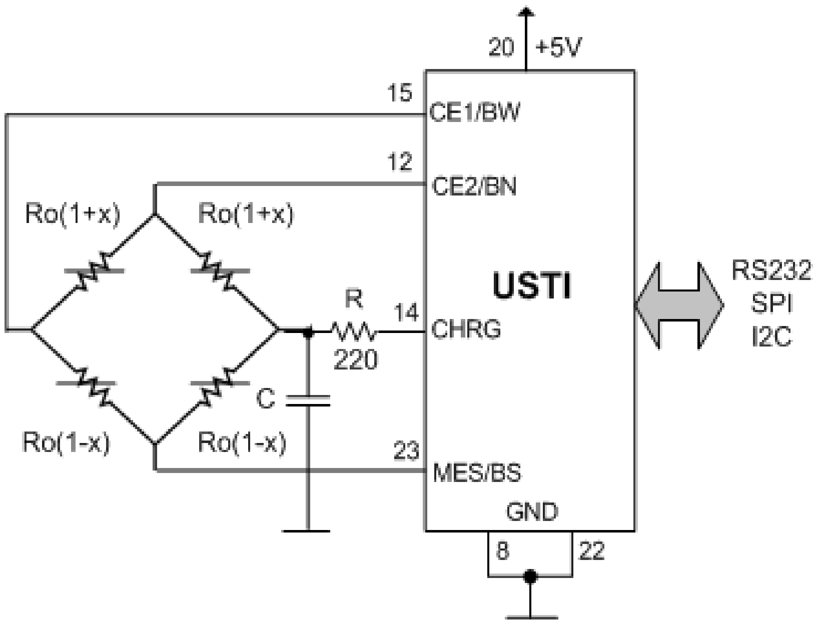


Fig. 3. Direct sensor-bridge to USTI connection for a full bridge (four acrive arms).

The converter has three popular serial interfaces RS232, SPI and I^{2}C for communication to PC or master microcontroller. The USTI can work in a slave communication mode with all mentioned serial interfaces and a master communication mode for RS232 communication. In this case, no any master microcontroller neither external PC should be used for IC controlling. The USTI continuously generates converted results at its output.

The following design consideration should be taken into account for the external components. The capacitance (in Farads) of capacitor C should be calculated according to the following equation:

$$C \ge \frac{0.002}{R_a}, \text{ (F)} \qquad (2)$$

where R_a is the resistance of a bridge arm. The charging time (in seconds) should be calculated as

$$T = 2200 \times C\,. \qquad (3)$$

The charging time can be set up with the help of USTI's command "Wnn".

An example of USTI's commands for resistance-bridge – to – digital conversion (RS232 serial interface, slave mode) is shown in Fig. 4.

```
>M12;          Set up a resistance-bridge Bx measurement mode
>W13;          Set the charging time 20 ms
>S;            Start measurement
>C;            Check result readiness. This command returns "b" if IC busy
               and "r" if the result is ready
>R;            Read conversion result
0.006005379986
```

Fig. 4. USTI's commands for resistance-bridge – to – digital conversion at RS232 communication slave mode.

In the master communication mode the charging time should be set up with the help of external switches N_0, N_1, N_2; and the mode - by M_0, M_1, M_2 jumpers at appropriate USTI's inputs (Fig. 5).

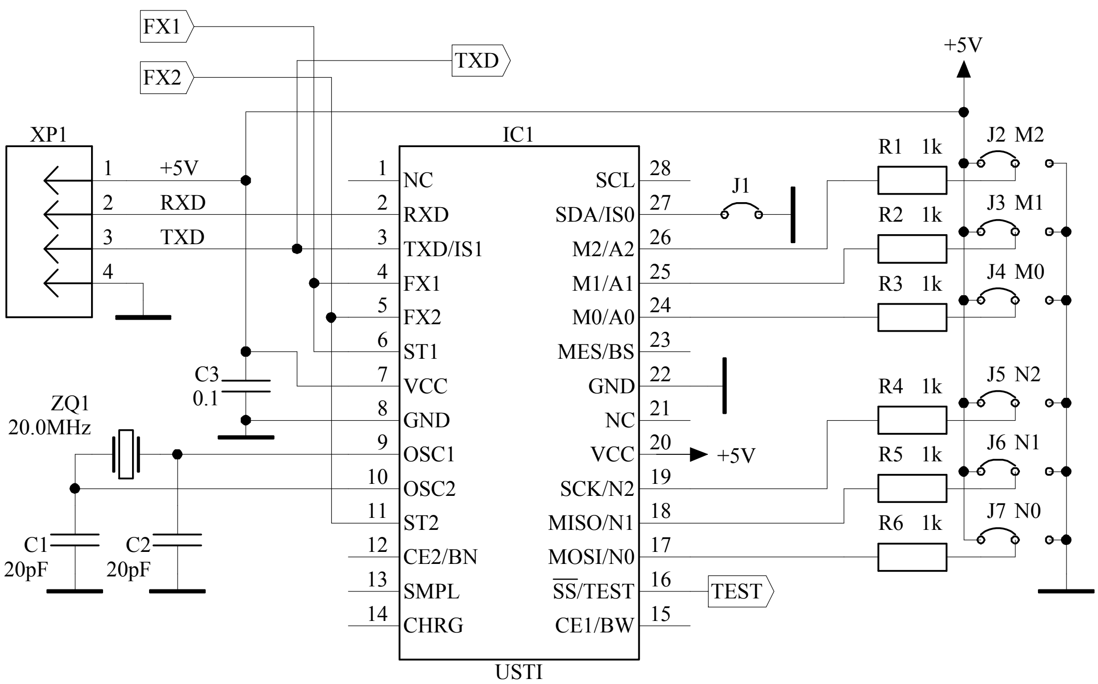


Fig. 5. Circuit diagram of USTI working in master mode (RS232).

The circuit diagram of USTI working in slave communication mode (RS232) controlled by an external microcontroller or PC is shown in Fig. 6.

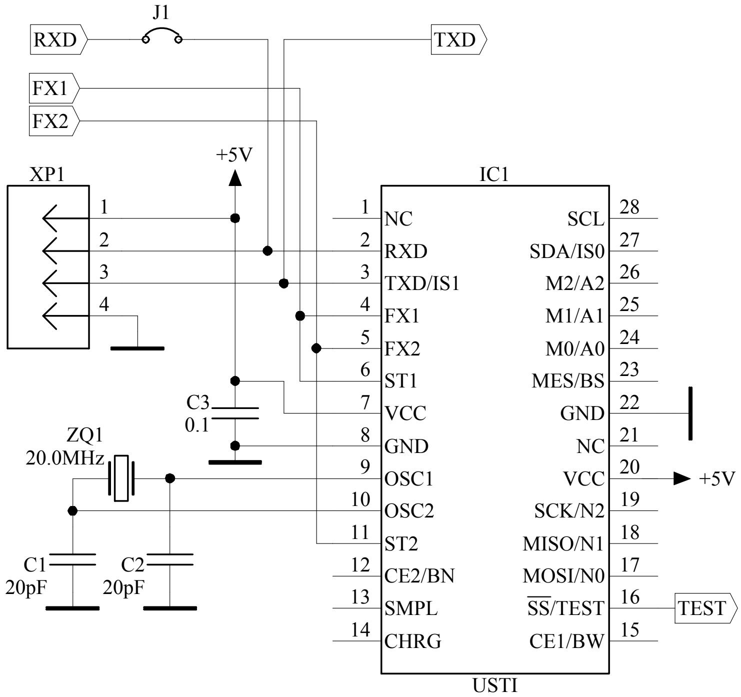


Fig. 6. Circuit diagram of USTI working in slave communication mode (RS232).

Oscillograms on the USTI's CHRG pin for C=1 μF and charging time 2 ms; and for C=2 μF and charging time 4 ms at measurement for a resistive-bridge low cost differential pressure sensor SX30GD2 (Honeywell) with input/output resistance 4.1 kΩ at atmospheric pressure in laboratory conditions are shown in Fig. 7 (a, b).

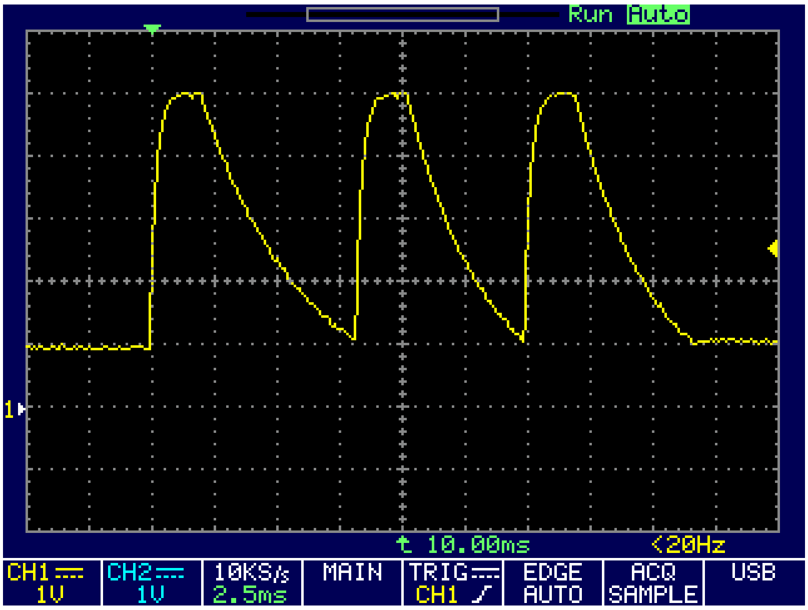
In the first case, the full length of one measuring cycle does not exceed 21.5 ms (without taking into account the communication and calculation times of IC); in the second case – 36 ms.

The relative quantization error for time interval measurement at each of discharging stage can be calculated according to the following equation:

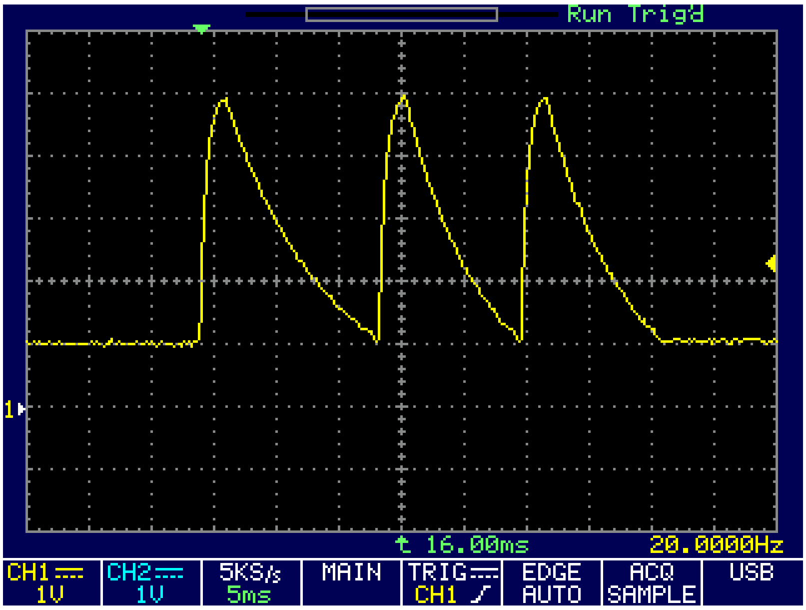
$$\delta_x = \frac{1}{f_0 \times t_x} \times 100 \ \%, \tag{4}$$

where f_0 = 20 MHz is the reference frequency for the USTI integrated circuit; t_x is the converted time interval. So, for the minimum discharge time ~5 ms (Fig. 7, a) the relative quantization error for discharge time measurement will not exceed 0.001 % and can be neglected in comparison with a sensor's error.

In addition, the designed universal resistive-bridge – to – digital converter can work with any known bridge – to –frequency or – duty-cycle converters, described, for example, in [10-17] and industrial sensor signal conditioners with PWM and period-modulated outputs, for example, ZMD31030/31050 (ZMDI), MAX1463 (Maxim), etc, and UTI (Smartec), Table 1. In such cases, their outputs of such converters should be directly connected to any of two USTI's channels for frequency-time measurements (pin 4, 6 or 5, 11). The 2-channel USTI can measure a frequency in a wide measuring range from 0.05 Hz to 9 MHz (144 MHz with prescaling) with programmable relative error from 1 to 0.0005 %. The relative error is constant in the whole frequency range. The converter has non-redundant conversion time for frequency and period measurements, and scalable resolution. The frequency-to-digital conversion error of the USTI can be also neglected in comparison with the bridge-to-frequency and sensor error.



(a)



(b)

Fig. 7. Oscillogram of three-point measurement technique at offset, reference and measurand determination charges-discharges stages on the CHRG pin: C=1 μF , charging time 2 ms (a); C=2 μF , charging time 4 ms (b).

In case when the condition circuit for resistive bridge sensors combines frequency and duty-cycle modulation of the same output signal, as described in [14, 16-17] it also can be directly connected to the designed universal resistive-bridge – to – digital converter because of the last one can convert both: frequency and duty-cycle into digital in the same channel.

The commands for frequency and duty-cycle measurements at RS232 slave communication mode for a resistive conditioning circuit are shown in Fig. 8.

```
>M00;              Set up a frequency fx measurement mode
>A09;              Select the relative error 0.001 %
>S;                Start measurement
>C;                Check if a result is ready
>R;                Read conversion result for fx
10000.0045879

>M04;              Set up a duty-cycle measurement mode
>S;                Start measurement
>C;                Check if a result ready
>R;                Read conversion result for duty-cycle
0.4532
```

Fig. 8. USTI's commands for frequency and duty-cycle measurements in the 1st channel at RS232 slave communication mode.

In the common case, two independent resistive-bridges – to – frequency condition circuits can be connected to the designed IC as well as one addition resistive sensor bridge. Such advantage is very useful and multichannel sensor systems and data acquisition systems design. Taking into account a small MLF package size (5 mm x 5 mm x 1 mm) such converters can be easily embedded into various sensors' packages to produce low cost universal digital solution.

3. Experimental Results

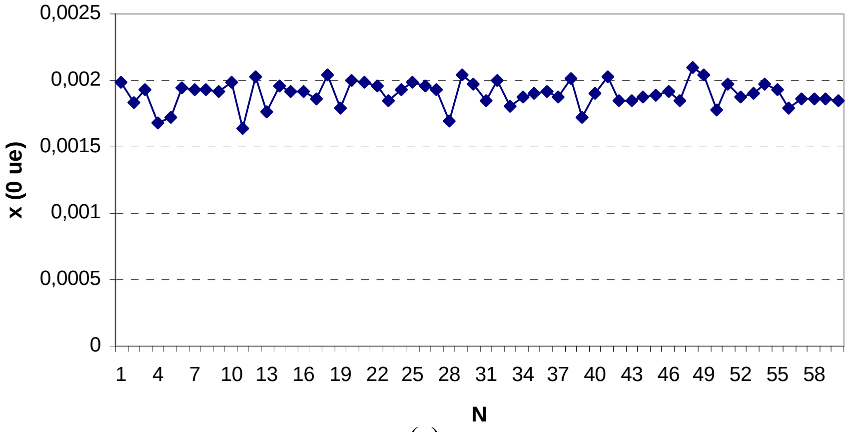
The circuit has been tested with both: a strain gauges bridge emulator and differential pressure resistive bridge sensor SX30GD2.

3.1. Strain Gages Emulation

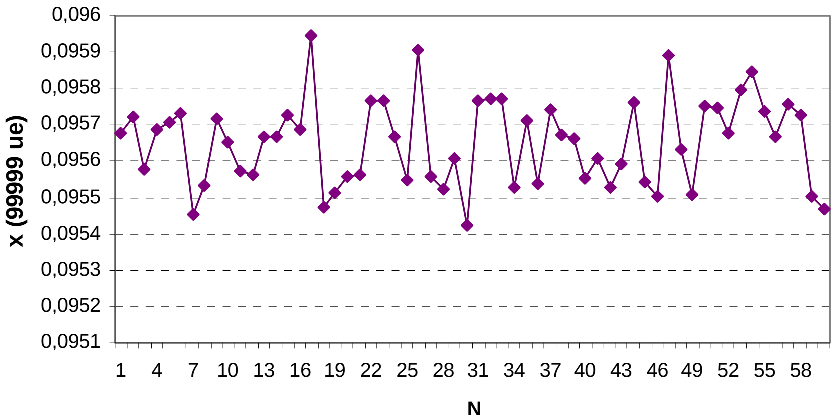
Preliminarily, the USTI has been calibrated at laboratory temperature range (+26.9 ^{0}C…+29.8 ^{0}C) in order to eliminate additional systematic error due to quartz oscillator trimming inaccuracy (calibration tolerance) and a short term temperature instability [21]. The USTI has been connected to a PC (through the serial RS232-to-USB interface) where the terminal software Terminal v1.9b was running under Windows.

The full resistive Wheatstone bridge sensor was emulated by the Strain Indicator Calibrator Vishay 1550A - a laboratory standard for verifying the calibration of strain and transducer indicators. It has the accuracy 0.025 % due to high precision ultra-stable Vishay resistors used throughout to ensure excellent stability, repeatability, accuracy and incremental steps required in a laboratory standards instrument. The calibrator reads directly in microstrain. The bridge resistance was 350 Ω. The value of capacitor C was calculated according to the equation (2): C = 0.002/350 = = 5.7 μF. In one's turn, the charging time was calculated according to formula (3): T=2200 × 5.7 μF ≅ 13.2 ms. The actual charging time was set up 20 ms with the help of USTI's W13 command (Fig. 4).

The strain gage range was changed at the experiment from 0 to ± 99 900 με with appropriate steps. Each of value was measured 60 times in order to compare obtained results with reported in literature It was visible changes for fractional resistance change *x* form approximately 0.018 (at 0 με) to 0.0995 (at 99 900 με). The measurement results for emulated strain gage ranges 0 με and 99900 με are shown in Fig. 9 (a, b). Statistical characteristics are adduced in Table 2.



(a)



(b)

Fig. 9. Measurement results for emulated strain gage ranges 0 με (a) and 99900 με (b).

Table 2. Statistical characteristics.

Parameter	**Value**	
	x (0 με)	**x (99900 με)**
Number of measurements, *N*	60	60
Minimum R_x (min)	0.0016	0.0954
Maximum R_x (max)	0.0021	0.0959
Sampling Range, R_x (max) - R_x (min)	0.0005	0.0005
Median	0	0
Arithmetic Mean	0.0019	0.0957
Variance	9.5E-0009	1.4E-0008
Standard Deviation	0.0001	0.0001
Coefficient of Variation	19.5202	803.946
χ^2 – test (S) at: k=6; P = 97 % χ^2_{max} = 8.9	2.2572	5.354
Hypothesis about Gaussian distribution	Accepted	Accepted

The χ^2-test for goodness of fit was applied to investigate the significance of the differences between observed data in the histograms and the theoretical frequency distribution for data from a normal (Gaussian) population. Taking into account that the sum of deviations between the data set and the assumed distribution in both cases $S > \chi^2_{max}$, (see Table 2), a hypothesis about the Gaussian distribution can be accepted in these two cases.

The dependence of fractional part *x* vs. emulated values in the whole strain gage range from 0 με to 99900 με is shown in Fig. 10. It is linear and has two sub ranges: (0 … 1000) με and (2000 …99900) με.

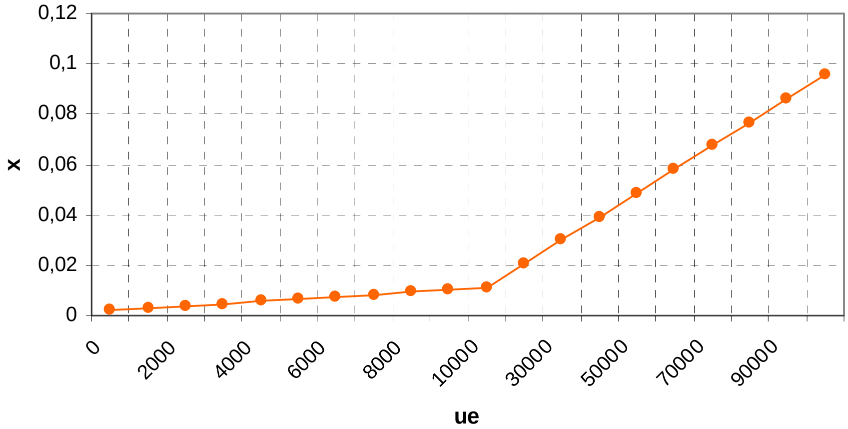


Fig. 10. *x* changes through the strain gage measuring range.

3.2. Differential Pressure Sensor Series SX30GD2

The sensor system consisting from the designed universal interfacing circuit for resistive-bridge sensors and a resistive differential pressure sensor bridge SX30GD2 (Honeywell), without any active component between the USTI and bridge also was investigated experimentally. The SX30GD2 is a low cost silicon differential pressure sensor with four-resistor bridge circuit. It has typical 0.2 % (0.5 % maximal) combined pressure non-linearity and pressure hysteresis FSS error and 0 … 30 psi operating pressure range and 4.1 kΩ bridge resistance.

Time intervals on the USTI's CHRG pin where measured 100 times with an external Schmidt trigger 74HC14D and without it (Fig. 11). *C* was 2 μF and charging time 4 ms.

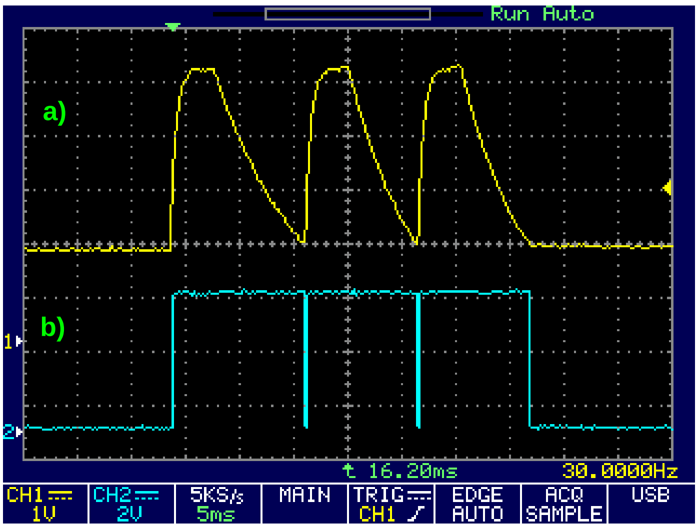
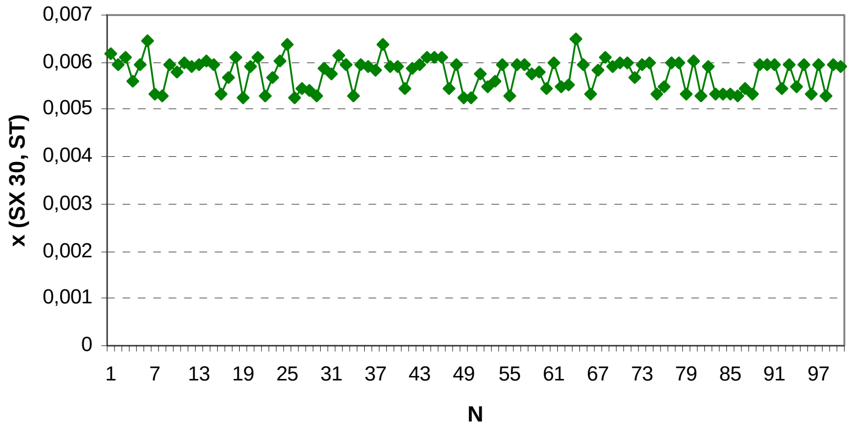
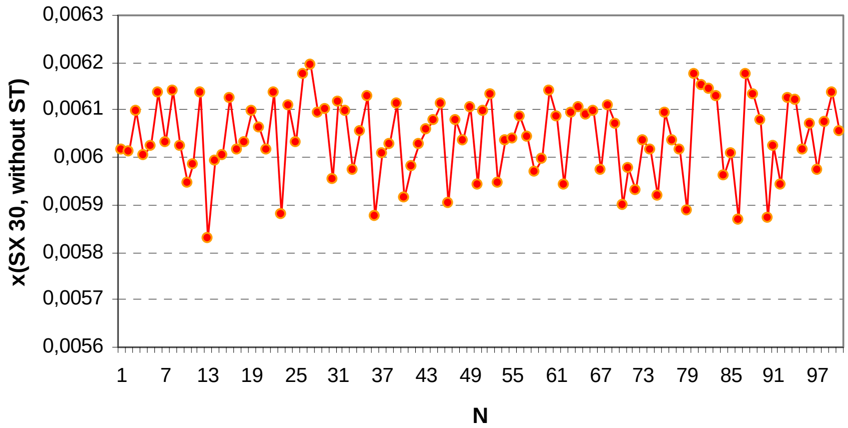


Fig. 11. Oscillograms on the USTI's CHRG pin without Schmidt trigger (a), and with external Schmidt trigger (b).

Measurement results for both cases at *p*=0 psi are shown in Fig. 12 (a, b) and statistical characteristics – in Table 3. As it visible form the experimental results the relative error in these both cases are practically the same and comparable or less to the sensor's error.



(a)



(b)

Fig. 12. Measurement results at 0 psi for sensor system with external Schmidt trigger (a), and wihtout Schmidt trigger (b).

4. Conclusions

An integrated universal resistive-bridge – to – digital converter is based on the Universal Sensors and Transducers Interface circuit and uses a simple, cost-effective three-point measuring technique. The converter can work with various resistive bridge sensors that do not include any internal components other than the arms forming a bridge.

In addition, the converter can work with any known resistance-bridge – to - frequency or duty-cycle converters and industrial sensor signal conditioners and interfacing circuits with PWM and period-modulated outputs. In such cases, their outputs should be directly connected to any of two USTI's channels for frequency-time measurements.

The designed IC has been realized in a standard CMOS technology as a low power ASIP. It has an industrial operating temperature range from – 40 ^{0}C to +85 ^{0}C. The power supply voltage is +4.5 … +5.5 V. The active supply current at operating voltage +4.5 V and clock frequency 20 MHz is not more than 9.5 mA.

Table 3. Statistical characteristics**.**

Parameter	**x (p = 0 psi)**	
	With Schmidt trigger	**Without Schmidt trigger**
Number of measurements, *N*	100	100
Minimum R_x (min)	0.0053	0.0058
Maximum R_x (max)	0.0065	0.0062
Sampling Range, R_x (max) - R_x (min)	0.0012	0.0004
Median	0	0
Arithmetic Mean	0.005757267	0.006041671
Variance	1.0E-0007	6.6E-0009
Standard Deviation	0.0003	0.0001
Coefficient of Variation	17.805	74.3148
Confidence interval for arithmetic mean at *P*=97 %	$0.0057 < x < 0.0058$	$0.006 < x < 0.0061$
Relative error, %	0.87	0.83
χ^2 – test (S) at: k=8; P = 97 % χ^2_{max} = 12	57.0539	7.4373
Hypothesis about uniform distribution	Not accepted	Accepted

The future research and development will be focused on the further improvement of metrological performance including conversion time, accuracy and extending the operating temperature range up to +150 ^{0}C in the future series of USTI ICs and various sensor signal conditioners on its basis.

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Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc.

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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- Virtual instruments;
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