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Distance Measurement System Based on Ultrasonic Smart Sensors and Universal Sensors and Transducers Interface (USTI)

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Abstract: This article presents a low cost, 2-channel, accurate ultrasonic sensor system based on smart HRLV-MaxSonar – EZ Series MB1013 ultrasonic sensor, HR-MaxTemp temperature sensor and Universal Sensors and Transducers Interface (USTI) integrated circuit. The experimental investigations have confirmed high metrological performances of the designed sensor system. It was shown that the quantization error of pulse width-to-digital conversion can be neglected in comparison with the sensor's error because of it is in 2-3 orders less than the sensor's error. Due to the high metrological performances and technical characteristics the developed ultrasonic sensor system can be used for any frequency-time parameters output (pulse width, frequency, PWM, etc.) ultrasonic sensors, existing on the modern market. The similar systems with the same metrological performances can be easily build also based on USTI-EXT, USTI-MOB, UFDC-1 and UFDC-1M-16 integrated circuits. The proposed sensor system is well suitable for such application as distance measurements; tank level measurements; objects, people and vehicle detections and monitoring; garage parking assistants; motion detectors, etc.

Keywords: Distance measuring system, Ultrasonic sensors, smart sensors, Universal Sensors and Transducers Interface (USTI), UFDC-1, HRLV-MaxSonar, MB1013, HR-MaxTemp sensor.

1. Introduction

Various types of sensors and sensing principles have been used to develop contactless distance measurement and object detection systems in the last decades. Each technique has their own advantages and disadvantages. In the previous paper [1] it was described a fist prototype of contactless distance measurement systems based on the infrared sensor. The system demonstrates a good accuracy and high resolution, but it has a limited measuring range from 5 to 200 mm. Similar performances are also achieved with the optical sensors. Microwave and laser based distance measurement systems have large measurement range, but low resolution and are expensive. An interesting inexpensive alternative, which has been proposed and investigated by several authors [2-6] is the use of ultrasonic sensors based on the time of flight technique. Such sensors are cheap enough and have a wide range of measurements from some centimeters to some meters.

According to the modern market study the ultrasonic sensors market was valued at US $ 3.63 billion in 2019 and is expected to reach a value of US $ 6.90 billion by 2025, at a CAGR of 11.35 %, from 2020 to 2025 [7]. Ultrasonic sensors are widely used to measure and detect various parameters, such as distance, position, presence, and level of an object.

Many various ultrasonic sensors from different manufacturers have analog, digital (serial data (either RS232 style or TTL style) or I^2C)) or quasi-digital (frequency (f_x) or pulse width t_x) outputs. While each output has its own benefits, some require more knowledge and equipment to use. Some other outputs are more accurate and robust than others. Despite the fact that the share of digital sensors on the modern sensor market is constantly increasing in the last decades, it is necessary to take into account also their essential disadvantages, in comparison with quasi-digital output sensors. So, digital signals are not suitable for dynamic monitoring due to the delay in signal conversion from analogue to digital and also the time for polling the sensor for readings. The quasi-digital signals are free from such disadvantages, easy interfacing, and are relatively resistant to a signal degradation from electrical noise, long cable runs, and other changes in cable resistance [8].

Ultrasound smart sensors with quasi-digital outputs are proposed by *Siemens* (3RG6421-3RS00 with 240...1600 Hz /60...400 Hz frequency output), Turk (M18, frequency output (LFX)), *Pepperl+Fuchs* (UB500-18GM75-F-V15, frequency and PWM outputs), *MaxBotix* (MaxSonar Series, pulse width output) and other manufacturers [9].

In this study, the distance measuring system was designed and implemented using the ultrasonic smart sensor HRLV-MaxSonar – EZ Series MB1013 [10] and Universal Sensors and Transducers Interface (USTI) integrated circuit [11].

2. System Design and Implementation

2.1 Ultrasonic Smart Sensor

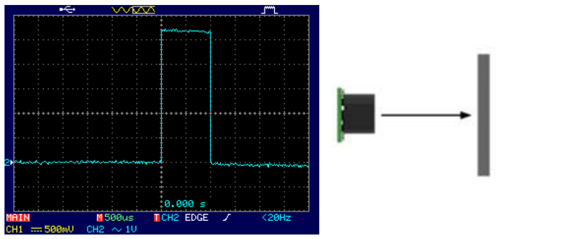
It was decided to use the low cost ultrasound sensor MaxBotix HRLV-MaxSonar–EZ Series MB1013 with a pulse width output [10]. The sensor is suitable for target distance from 30 cm to 5 m [10]. The width of the high pulse directly corresponds to the distance range (1 µs/mm). A narrower high pulse indicates a lower range, and a wider high pulse indicates a larger range (Fig. 1).

The output range of this sensor is 300 µs for 300 mm to 5000 µs for 5000 mm. The pulse will be at 0-V_{cc} voltage logical levels. The sensor has 1 mm resolution and ± 0.1 % relative error at ± 1 m and a typical large target relative error ± 1 %.

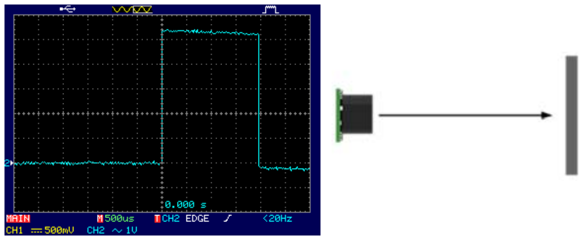
In general, the velocity of sound in air depends on the temperature T_c and on the air humidity h:

$$V_s = f\left(T_c, h\right) \qquad (1)$$

Although the HRLV-MaxSonar-EZ sensor has an internal temperature sensor, it is recommended to use the optional external HR-MaxTemp sensor for the best accuracy [12]. This temperature sensor allows HR-MaxSonar to have an automatic external temperature compensation for changes in the speed of sound due to temperature. The external temperature sensor allows for the most accurate temperature compensation, by eliminating sensor self-heating from the sensor electronics, and by allowing to place the temperature sensor closer to the center of the acoustic ranging path. The actual operating temperature range of the HR-MaxSonar is from -40 ºC to +65 ºC, and recommended operating temperature range is from -15 ºC to +65 ºC.



(a)



(b)

Fig. 1. Sensor's output oscillograms at 1 m (a), and 2 m (b) distances.

The distance at the temperature compensation is calculated according to the following equation [13]:

$$D_m = T_{of} \times \frac{20.05 \times \sqrt{T_c + 273.15}}{2}, \qquad (2)$$

where T_{of} is the measured time of flight in [s], T_c is the ambient temperature in [ºC].

The most power related electrical noise influences can be eliminated by adding a 100 µF capacitor between the +V and GND pins.

2.2 Sensor Interfacing Circuit

A sensor interfacing circuitry plays essential role in any sensor system design. Namely this unit brings additional errors to the measuring channel in addition to the sensor's error itself.

Although quasi-digital sensors are easy interfacing and can be directly connected to any low cost microcontrollers, a frequency- or pulse width – to– digital conversion methods are bottlenecks in many designs and implementations due to high quantization errors, limited measuring range and redundant conversion time of standard counting techniques [14]. In many cases it is necessary to use so-called advanced methods of measurements for frequency-time paramagnets of sensors' outputs. As usually, such methods are patented.

It was decided to use the Universal Sensors and Transducers Interface (USTI) IC [10] in this implementation. The USTI has a special mode for pulse width measurement (t_p) in the range from 1.5 µs to 250 s. The pulse signal must come on the FX1 and ST1 USTI's inputs [11].

The quantization error at pulse width measurements can be calculated according to the following equation:

$$\delta_q = \frac{1}{20 \cdot 10^6 \cdot t_p} \times 100\,\% \qquad (3)$$

Taking into account the HRLV-MaxSonar-EZ sensor's output 300 … 5000 µs, the appropriate USTI's quantization error at pulse-width measurements will be in the following range: $\delta_q \in \pm[0.001 \div 0.017]$ %. Such error can be neglected in comparison with the sensor's error, because of it is more than in 5-10 times less than the sensor's error itself $\pm[0.1 \div 1]$ % [15].

The USTI has three popular communication interfaces: SPI, I2C and RS232/USB and two input channels. So, two HRLV-MaxSonar–EZ sensors can be directly connected to the same USTI IC.

The RS232 commands for USTI working in pulse-width measurement mode are shown in Fig. 2.

```
> M0B  ;Select pulse-width measurement mode
> S    ;Start measurement
> C    ;Check the result ('r' - ready, 'b' – in progress)
> R    ;Read result in [µs].

1000.893528
```

Fig. 2. RS232 Commands for the USTI working in pulse-width measurement mode.

Instead of the USTI IC, the Universal Frequency-to-Digital Converter (UFDC-1 and UFDC-1M-16) Series ICs as well as the USTI-EXT (IC version for extended temperature range) and USTI-MOB (low power version) can be used for the HRLV-MaxSonar–EZ sensors interfacing. The relative errors of each of mentioned IC Series are shown in Table 1.

Table 1. Quantization errors of ICs working in pulse width measurement mode in 300-5000 µs measurement range.

Series IC	Range	Quantization Error, %
USTI	1.5 µs … 250 s	0.0010 … 0.0170
USTI-EXT	2 µs … 250 s	0.0013 … 0.0210
UFDC-1	2 µs … 250 s	0.0013 … 0.0210
UFDC-1M-16	2 µs … 250 s	0.0013 … 0.0210
USTI-MOB	7 µs…1000 s	0.0050 … 0.0830

The UFDC-1 development board, HRLV-MaxSonar–EZ and HR-MaxTemp sensors connections are shown in Fig. 3.

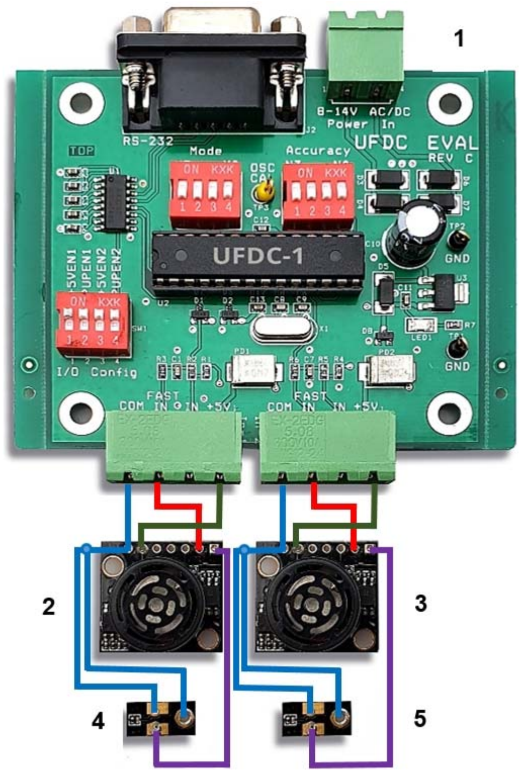


Fig. 3. Connection of the UFDC-1 Development Board (1) with two HRLV-MaxSonar–EZ MB1013 (2, 3) ultrasonic sensors and two HR-MaxTemp temperature sensors (4, 5).

3. Experimental Set-Up

The diagram of experimental measurement set-up for the ultrasonic sensor system based on the USTI Development board and HRLV-MaxSonar–EZ MB1013 smart sensor is shown in Fig. 4. The distance between the sensor and a target object, controlled by a measurement tape, was changed from 30 to 250 cm. In order to eliminate the sound velocity changes due to the variation of air temperature, the external HR-MaxTemp sensor MB7957 has been used [12].

A square waveform pulse signal whose pulse width must be measured, were fed from the HRLV-MaxSonar–EZ MB1013 sensor output (pin 2) to the inputs FX1, ST1 of the 1st channel of USTI IC running on a 20 MHz clock.

The supply voltage of the USTI development board was +14 V dc, provided by the Promax FA-851 power supply. The pulse width of the sensor's output signal were measured by both: the USTI and Universal Frequency Counter/Timer Agilent 53220A working in the pulse width measurement modes. The Frequency Counter has the ultra-high oven stability internal time base with uncertainty ± 100 ppb (± 0.00001 %) [16]. The digital oscilloscope Promax OD-591 monitored the signal waveform.

Before measurements, the USTI was calibrated in the working temperature range: +24.2…+ 26.1 ºC at 52-58 % RH. The measurands were sent to a PC via the RS232/USB interface implemented with the ST202D IC and RS232-USB converter EMINENT EM 1016. The user interface was realized with the help of terminal software Terminal V1.9b running under the Windows 10 operation system. As usually, every measurement were consisted of 100 values (sample size n=100). The measurement errors of pulse width measurements were evaluated from appropriate statistics.

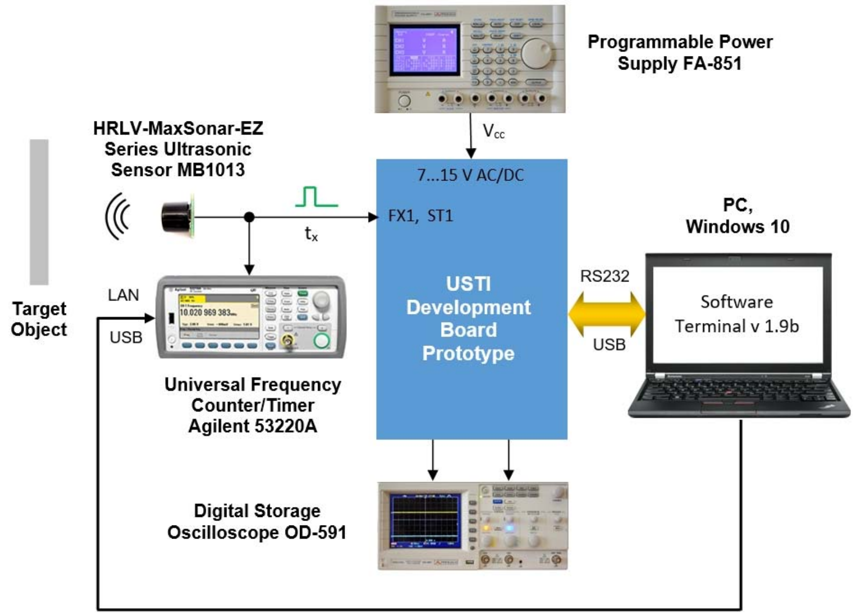


Fig. 4. Experimental measurement set-up for the ultrasonic sensor system.

4. Experimental Results

During the experimental investigation, the measurements have been made for the following distances (100 times for each value): 30 cm, 60 cm, 100 cm, 200 cm and 250 cm. The conventional true values for the pulse widths corresponded to these distances have been measured by the Universal Frequency Counter/Timer Agilent 53220A. Oscillograms of sensor's output at 30 cm (min) and 5 m (max) are shown in Fig. 5 and 6. The measurement results are shown in Fig. 7-11.

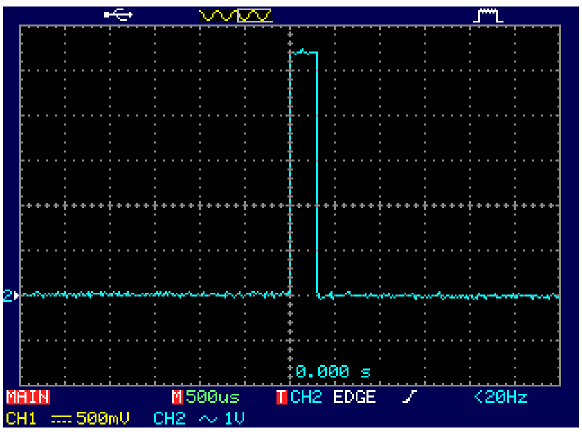


Fig. 5. Oscillogram at sensor's output at 30 cm distance.

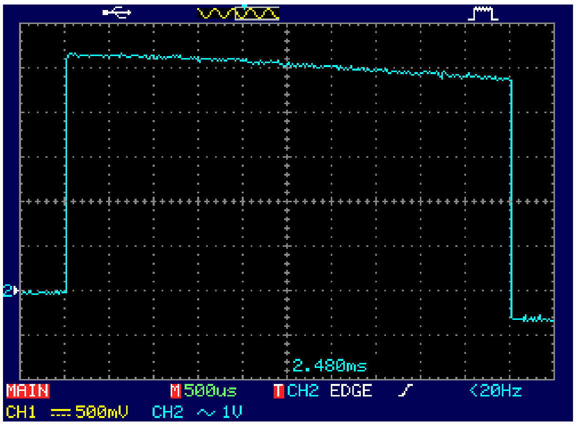
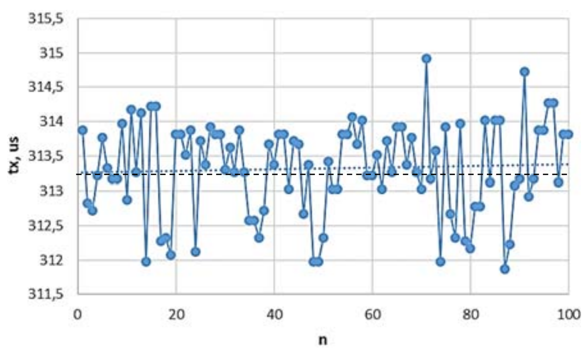
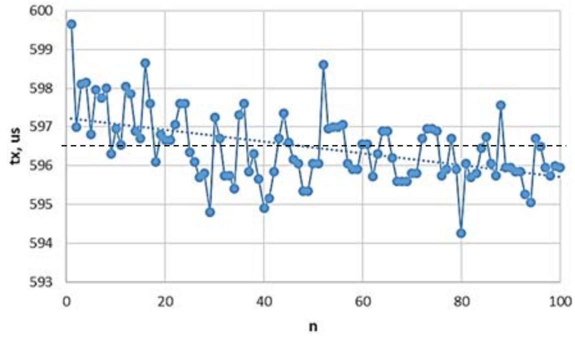


Fig. 6. Oscillogram at sensor's output at 5 m distance.



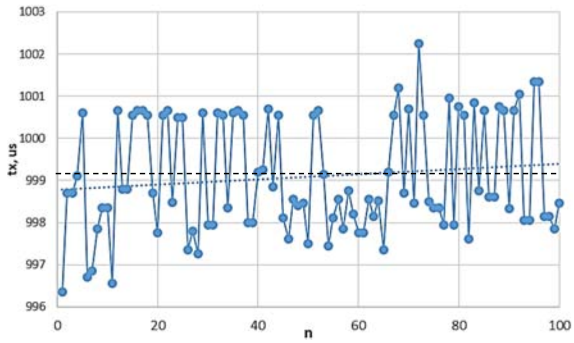
--- average value; ··· trend.

Fig. 7. Measurement results for pulse width at 30 cm.



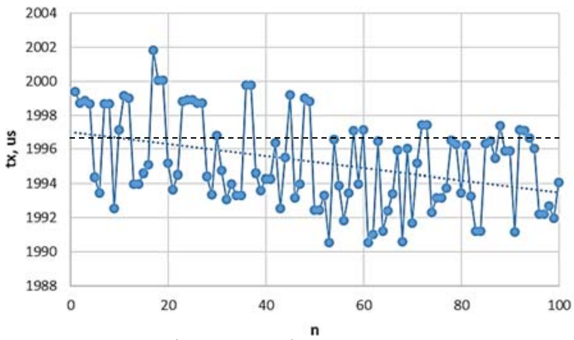
--- average value; ··· trend.

Fig. 8. Measurement results for pulse width at 60 cm.



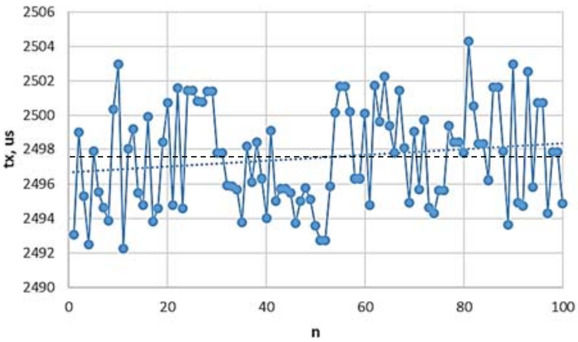
--- average value; ··· trend.

Fig. 9. Measurement results for pulse width at 1 m.



--- average value; ··· trend.

Fig. 10. Measurement results for pulse width at 2 m.



--- average value; ··· trend.

Fig. 11. Measurement results for pulse width at 2.5 m.

The measurement errors were evaluated from appropriate statistics with the help of NUMERI software [18]. The statistical characteristics are adduced in Table 1. The number of intervals grouping of experimental data were selected according to the following equation [15]:

$$m_{\min} = 0.55\, n^{0.4} \quad \text{and} \quad m_{\max} = 1.25\, n^{0.4}, \tag{4}$$

where n is the sample size. For n=100, the numbers of intervals grouping of experimental data m are the following: m_{min} = 4 and m_{max} = 8 and the value m=7 has been selected according to the recommendations given in [15].

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 a normal, uniform or exponential population. If $S < \chi^2_{max}$, where S is the sum of deviations between the dataset and the assumed distribution, and χ^2_{max} is the maximum possible allowable deviation in the χ^2 distribution, the hypothesis of appropriate distribution can be accepted [18]. The χ^2 test has been used at 95 % confidence.

The appropriate relative errors vs. distance are shown in Fig. 12. The relatively high error (±0.25…0.79 %) between 30 and 60 cm can be explained by the acoustic phase effect in the near field mentioned in [10]. However, in any case, the relative error does not exceed the declared by *MaxBoticx, Inc.* sensor's error ± 1 % [10].

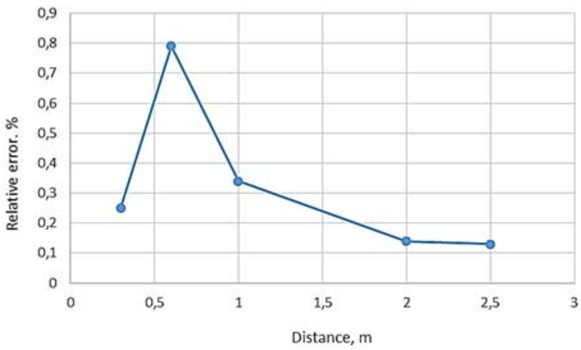


Fig. 12. Relative errors vs. distance.

Nevertheless the range of distance, which can be measured by the HRLV-MaxSonar–EZ ultrasonic sensor is from 30 cm to 5 m, the sensor can detect objects (but not to measure the distance) from 1 mm to 30 cm. In this case the pulse width of rectangular pulse on the sensor's output will be the same, and corresponds approximately to 30 cm distance.

Table 1. Statistical characteristics of measurement results.

Distance / Parameter	30 cm	60 cm	1 m	2 m	2.5 m
Minimal t_x (min), µs	312.9231	594.2540	996.3552	1990.5608	2492.2376
Maximal t_x (max), µs	315.3225	599.6526	1002.2537	2001.8081	2504.2846
Sampling Range, t_x (max) - t_x (min), µs	2.3994	5.3987	5.8986	11.2472	12.047
Median	0	0	0	0	0
Arithmetic Mean, µs	314.0678	596.4637	999.0982	1995.2471	2497.5136
Variance, µs	0.4051	0.8236	1.8298	7.2851	8.6673
Standard Deviation, µs	0.6365	0.9075	1.3527	2.6991	2.9440
Coefficient of Variation	493.4369	657.2627	738.5865	739.2291	848.3314
Confidence Interval at probability P=95 %	$t_x \in$ [313.943 ÷ ÷ 314.1925]	$t_x \in$ [596.2859 ÷ ÷ 596.6416]	$t_x \in$ [998.8331 ÷ ÷ 999.3633]	$t_x \in$ [1994.718 ÷ ÷ 1995.7761]	$t_x \in$ [2496.9365 ÷ 2498.0906]
Maximal Relative Error, δ_x %	$\leq \pm 0.25$	$\leq \pm 0.79$	$\leq \pm 0.34$	$\leq \pm 0.14$	$\leq \pm 0.13$
Distribution low:	$S <> \chi^2$				
- Normal	S= 10.78 > > χ^2=9.4 (rejected)	S=3.25 < < χ^2=9.4 (accepted)	S=50.90 > > χ^2=9.4 (rejected)	S= 32.34 > > χ^2=9.4 (rejected)	S=9.19 > > χ^2=9.4 (rejected)

5. Time of Measurement

Another important metrological performance of any sensor and sensor system is the time of measurement or measurement cycle. The measurement cycle of the HRLV-MaxSonar–EZ sensor is T_{sensor} = 100 ms [10]. The time of measurement for the USTI IC can be calculated according to the similar methodology, described by the author in [8, 17].

The time of measurement of USTI ($T_{meas\ USTI}$) includes three main components:

$$T_{meas\ USTI} = t_{conv} + t_{comm} + t_{calc}, \tag{5}$$

where t_{conv} is the conversion rate, t_{comm} is the communication time and t_{calc} is the calculations time. At the pulse width measurements the conversion rate equals to the pulse width: $t_{conv} = t_x$= 0.3 … 5 ms. The communication time t_{comm} for a slave communication mode (RS232 interface) can be calculated according to the following equation:

$$t_{comm} = 10 \cdot n \cdot t_{bit}, \tag{6}$$

where t_{bit} = 1/300, 1/600, 1/1200, 1/2400, 1/4800, 1/9600, 1/14400, 1/19200 or 1/28800 is the time for one bit transmitting; n is the number of bytes (n=13…24 for ASCII format). In the experimental set-up (Fig. 4) the baud rate was 1/2400. So, t_{comm} = 54 … 100 ms. In the common case, the calculation time depends on operands and as usually is $t_{calc} \leq$ 4.5 ms for frequency/period measurements. But it is at least in two times less for the pulse width measurements. Finally, the measurement cycle can be calculated as:

$$T_{meas} = T_{sensor} + T_{meas\ USTI} \tag{7}$$

In the case of 1/2400 baud rate, which was used in the experimental set-up the T_{meas}=160…205 ms.

6. Interfacing with Frequency Output Ultrasonic Sensors

Any ultrasonic frequency output sensor, existing on the modern market can be directly interfaced to the USTI, USTI-EXT, USTI-MOB, UFDC-1 and UFDC-1M-16 integrated circuits working in frequency measurement modes. All ICs have two channels for frequency-time parameters measurements. In order to connect more than two sensors to the single ICs, a simple digital multiplexer should be used [14].

Taking into account that the relative error for this modes can be selected from 0.0005 to 1 %, it must be chosen in 5-10 times less in comparison with the sensor's error to be neglected.

The RS232 commands for the USTI IC working in the frequency measurement mode with 0.01 % relative error are shown in Fig. 13.

```
> M00 ;Select frequency measurement mode
> A06 ;Select 0.01 % relative error
> S   ;Start measurement
> C   ;Check the result ('r' - ready, 'b' - in progress)
> R   ;Read result in [Hz].

1500.999519
```

Fig. 13. RS232 Commands for the USTI working in frequency measurement mode.

The first two commands should be used at once, and the rest three commands– in a cycle.

7. Conclusions

The experimental investigations of the designed 2-channel, low cost ultrasonic smart sensor system have confirmed its high metrological performances. The average relative error is ±0.33 % and the worst case error does not exceed ±0.79 % in the distance range from 30 cm to 2.5 m.

The sensor system based on the USTI, USTI-EXT, USTI-MOB, UFDC-1 and UFDC-1M-16 integrated circuits can be easy interfaced with any existing ultrasonic sensor with frequency, pulse width and PWM output. The frequency-time parameters-to-digital conversion error in such sensor systems can be neglected in comparison with the sensors' errors itself, because of it can be selected in 5-10 time less than the sensor's error.

The designed sensor systems can be used for distance measurements; tank level measurements; objects, people and vehicle detections and monitoring; garage parking assistant; motion detectors, etc.

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