Non-contact, short distance measuring system for wide applications

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NON-CONTACT, SHORT DISTANCE MEASURING SYSTEM FOR WIDE APPLICATIONS

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Abstract − A low-cost, accurate, non-contact, short distance measuring system is described in the paper. It includes a standard infrared light source, infrared light-to-frequency converter and specially designed for such applications the Universal Sensors and Transducers Interface (USTI) integrated circuit. In comparison with existing solutions, the designed measuring system has extended distance measuring range from 5 to 200 mm, 0.01 mm resolution, ±0.02 mm absolute error and a short conversion time that does not exceed 26.35 ms. Performance improvements are achieved due to a novel, precision modified method of the dependent count for frequency measurements with a non-redundant conversion time, which is used in the USTI.

Keywords: distance measurement systems, optical sensors, universal sensors and transducers interface

1. INTRODUCTION

Complex processes of industrial automation and robotic systems need information about placement of different objects. For this purpose noncontact distance measuring systems are used for placement and distance determination. As usually, existing measuring systems are based on laser ultrasonic or radar devices [1], and complete measuring systems cost some hundred dollars. The low measuring range for such sensor systems are limited by 15-20 mm [1]. Relatively low-cost measuring systems based on inductive displacement sensors have practically unlimited low measuring range (~ 2 mm) but the limited high measuring range up to 10-20 mm [1]. However, all of these sensor systems have high resolution, accuracy and short reaction time.

Low-cost short distance measuring systems with a price up to some tens dollars can be built based on the optical principle, infrared light sources as IRED and appropriate infrared light-to-frequency converters [2]. Such systems are using infrared optical sensors with output signal proportional to a distance between sensing element and object. For example, a low-cost short distance measuring system described in [3] uses frequency output optical sensor (infrared light source and infrared light-to-frequency converter), has 35-60 mm measuring range, and measuring time from 0.25 to 1 s.

Frequency output sensors have many advantages in comparison with analog (voltage or current) output sensors. It is a vide dynamic range of input light over 100 dB, which is not limited by the voltage supply; high noise immunity due to very high the signal-to-noise ratio; and minimum possible component interface [3, 4].

Very often in industrial automation and robotic systems it is necessary to measure distance from some millimeters to some tens centimeters with a high speed by a non-contact reflected light way. Existing industrial sensors and measuring systems [1] do not cover the mentioned distance range (typically, their measuring range is beginning from 10 mm) or/and they are relatively expensive. In order to overcome these disadvantages, an inexpensive, noncontact distance measuring systems with extended measuring range and high measuring speed was built and tested.

2. MEASURING SYSTEM'S COMPONENTS

The designed measuring system consists on an infrared light source (IRED), infrared light-to-frequency converter (IR LFC) TSL245R [5] and Universal Sensors and Transducers Interface (USTI) integrated circuit [6] especially designed for such applications. The infrared light-to-frequency converter combines a silicon photodiode with square area of 1.36 mm^2) and a current-to-frequency converter on a single monolithic CMOS integrated circuit. The output is a square wave (50 % duty cycle) with a frequency directly proportional to the light intensity. Because the output is TTL compatible, it allows direct interface to the USTI. The IR LFC is characterized for operation over the temperature range of −25°C to 70°C and is supplied in a 3-lead plastic side-looker package with an integral visible-light cutoff filter and lens [5]. The device responds over the infrared light range of 800 nm to 1100 nm and has a wide frequency range from ~0.4 Hz (dark frequency) to ~500 kHz.

The output frequency can be calculated according to the following equation:

$$f_O = f_D + (Re)\,(Ee), \qquad (1)$$

where f_O is the output frequency; f_D is the output frequency for dark condition (Ee = 0); Re is the device responsivity for a given wavelength of light given in kHz/(μW/cm^2); Ee is the incident irradiance in μW/cm^2.

The optical sensor operates with reflections. The light emitted by the IRED is reflected by the target object and a fraction of it comes back and is detected by the IR LFC. More signal is reflected when an object is closer. The output

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of the sensor reveals the distance of an object. The light intensity is converted into a frequency by means of current-to-frequency converter and then the USTI converts the frequency to digital according to one of three popular serial interfaces: RS232, SPI and I^2C. The circuit diagram of sensor system is shown in Fig. 1.

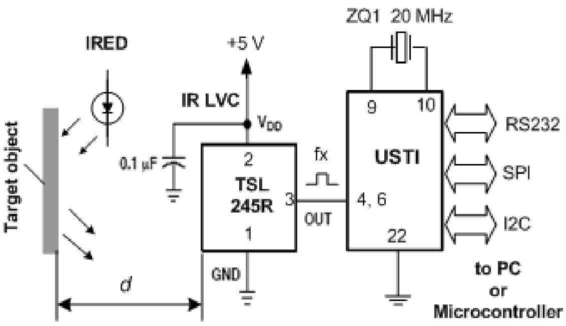


Fig. 1. Short distance measuring system: *d* - a distance to be measured; IRED - infrared light source; IR LFC - infrared light-to-frequency converter; USTI- Universal Sensors and Transducers Interface.

The USTI is a multifunctional, 2-channel IC with 29 measuring modes for any frequency-time parameters of electric signal and based on four novel patented measuring methods for frequency (period), frequency (period) ratio, duty-cycle and phase-shift. It has a constant programmable relative error of measurement from 1 to 0.0005 % in a wide frequency range from 0.05 Hz to 9 MHz without prescaling and to 144 MHz with prescaling. The USTI has non-redundant conversion time that is determined only by the programmable relative error δ. The resolution of this device is scalable and can be changed from to 2.5×10^{-7} to 45 Hz depend on the measuring range.

The time for frequency-to-digital conversion for the USTI should be calculated according to the following equation:

$$\begin{cases} t_{conv} = \dfrac{1}{f_x} \quad if \quad \dfrac{N_\delta}{f_0} \prec T_x \\ t_{conv} = \dfrac{N_\delta}{f_0} + (0 \div T_x) \quad if \quad \dfrac{N_\delta}{f_0} \geq T_x \end{cases}, \qquad (2)$$

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 the USTI [6].

In addition to the t_{conv} a common measurement time T_{meas} for the USTI must include also a communication time t_{comm} and calculation time t_{calc}. The communication time for a slave communication mode (RS232 interface) can be calculated according to the following formula:

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

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 transmitting; n is the number of transmitted bytes (n=13…24 for ASCII format). As usually, at the right chosen baud rate (maximum possible for a certain application) the $t_{comm} \leq t_{conv}$.

The communication time for SPI interface should be calculated as:

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

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 speed for I^2C interfaces can be determined according to the following equation:

$$t_{comm} = 8 \cdot n \cdot \frac{1}{f_{SCL}}, \qquad (5)$$

where f_{SCL} is the serial clock frequency, which should be 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 as usually is $t_{calc} \leq 3.6$ ms.

The appropriate commands for USTI working in the RS232 slave communication mode and measuring the frequency are shown in Fig. 2.

```
> M00    ;Frequency measurement in the 1st channel
> A06    ;Relative error set up (δ = 0.01 %)
> S      ;Start measurement
> C      ;Check the USTI status (b-busy, r-ready)
> R      ;Read result fx:
191063,5233
```

Fig. 2. USTI commands for frequency measurement (RS232 slave communication mode).

Due to a wide dynamic range, high accuracy and non-redundant conversion time the USTI is well suited for low-cost, non-contact short distance measuring systems.

3. EXPERIMENTAL RESULTS

The measurement set up is shown in Fig. 3. Both IRED and IR LFC are mounted on the TAOS LTF EVM TSL245R daughterboard installed in the sockets B of the LTF EVM motherboard [7], which was connected to a PC with the help of USB interface. For one's turn the motherboard with the daughterboard were mounted on the electronic digital caliper Z22855 Powerfix, which was used for distance set up and measurement with the absolute error ± 0.02 mm and resolution ± 0.01 mm (Fig.4).

The USTI was calibrated before at +22.7 ^{0}C (calibration constant is Δ_f = 10002493.9580 Hz) in order to eliminate a systematic errors due to trimming inaccuracy (calibration tolerance) and aging for the low-cost, 20 MHz quartz crystal oscillator and short time temperature instability [8]. The sensor system was supplied at +5V dc by a Promax FAC-363B power supply. Digital oscilloscope OD-571 was used for signal waveforms monitoring. The measured by USTI frequency values were sent to a PC via an RS232 interface implemented with the ST202D integrated circuit mounted together with the USTI on evaluation board. The high precision calibrated universal counter Agilent 53132A with the ultra high stability oven with temperature stability $<2.5\times10^{-9}$ was used for comparative precision measurements of frequency at the TSL245R output in parallel with the USTI.

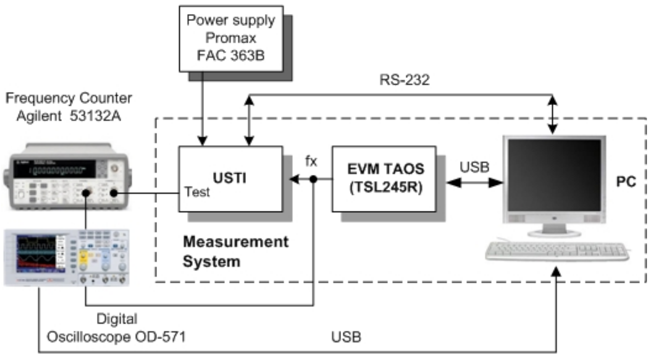


Fig. 3. Measurement set up.

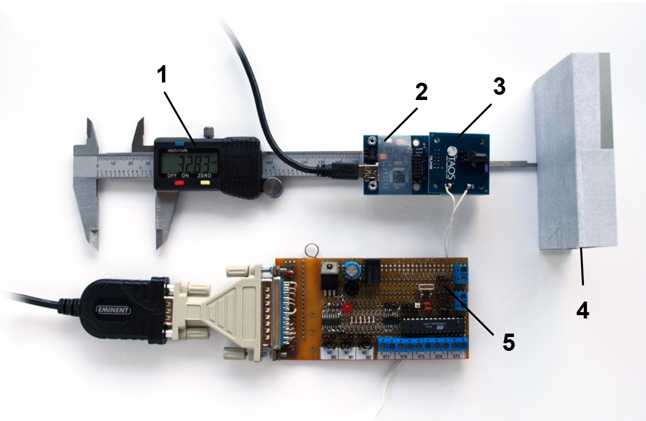


Fig. 4. A short distance sensor system: 1- electronic digital caliper Z22855 Powerfix; 2- LTF EVM motherboard; 3- TAOS LTF EVM TSL245R daughterboard; 4-target object; 5-USTI Evaluation Board.

The Graphical User Interface (GUI) was implemented with the help of terminal software Terminal V1.9b for Windows and TAOS LTF EVM software (Fig. 5). The Terminal V1.9b was used for connection and data exchange between the USTI and PC according to the RS232 interface, and the LTF EVM software was use for connection and data exchange between the motherboard, daughterboard and PC according to the USB interface. In addition, the LTF EVM software was used for rough measurements of frequency at the TSL245R output.

Measurements were made from 1.5 to 215 mm distances range. The frequency on the sensor's output was changed proportional to the reflected light and measured in the ~1.8 kHz to 190 kHz frequency range for a target object with the standard calibration reflective surface (18 % reflective gray paper, for which most sensors are calibrated), Fig. 6.

The measuring results are shown in Fig. 7. The graph shows a peak frequency measurement at a distance just a few millimeters from the detector. The response drops at shorter distances because there is space between the emitter (IRED) and detector (IR LFC). The closeness of the object reduces the amount of IRED light that can reflect to the IR LFC.

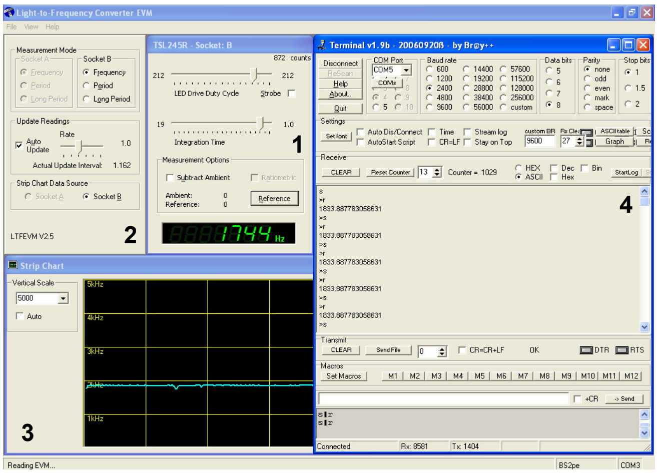


Fig.5. GUI measuring software: LTF EVM software: 1 -daughterboard window; 2- window with a control section; 3 - strip chart recorder window; 4 - Terminal V1.9b for Windows.

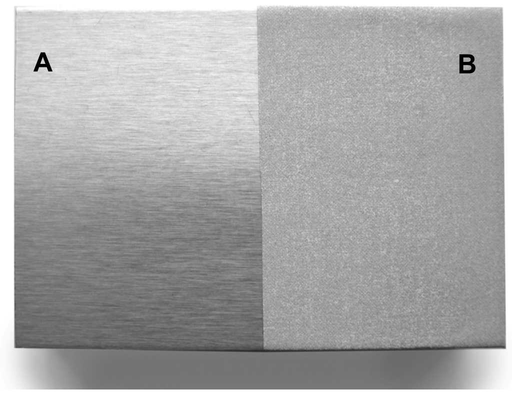


Fig. 6. Target object with the duraluminium surface (a) and standard calibration reflective surface (b).

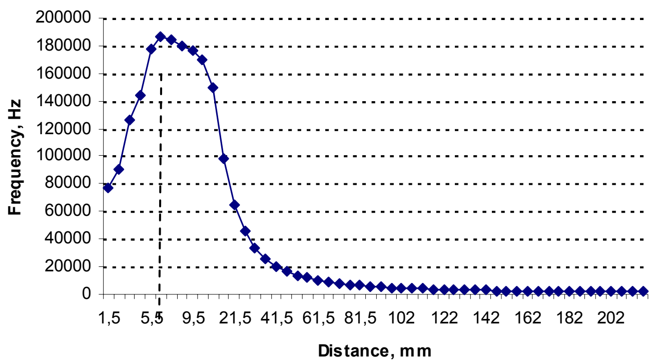
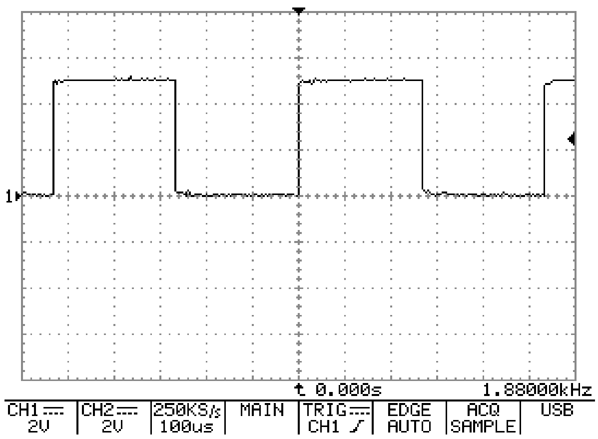


Fig.7. Distance from target object to sensing element (IR LFC).

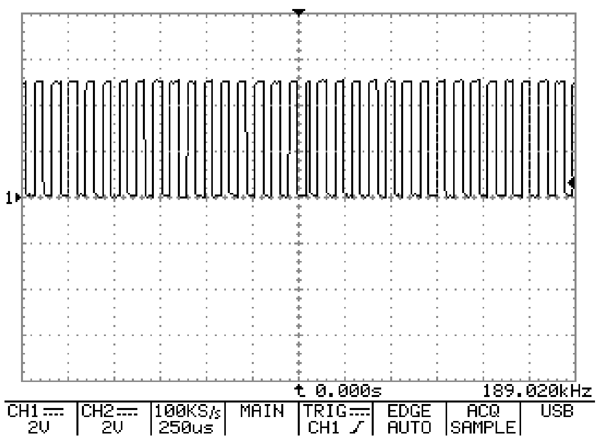
In the case if a target object is made from the duraluminium (Fig.6, b) more light is reflected from the object's higher reflectivity surface and output frequency will be increased in 3 times. In turn, the full scale of distances also will be increased a little.

The determined resolution for this measuring system is 0.01 mm, and response at 75 mm, for example, is 34 Hz/0.01 mm. The time of measurement calculated according to the equations (2), (3) for the RS232 interface communication at 38400 baud rate and 0.01 % programmable relative error is not more than $T_{meas\ max}$ = 26.35 ms, where t_{conv} = 16.5 ms, t_{comm} = 6.25 ms and t_{calc} = 3.6 ms. This time of measurement is less in 3.4 times in comparison with the conversion time of charge-balancing integrating type 16-bit ADCs (90 ms typical), that are used in various light-to-digital converters [9]; and less in 9.5 – 38 times in comparison with measuring systems described in [3].

Maximal and minimal frequencies at the sensor's output (Fig. 8 a, b) also were measured by the USTI with the minimum possible constant relative error δ = 0.0005 %.



a)



b)

Fig.8 Oscillograms at sensor's output at $f_{x\ min}$ = ~ 1.83 kHz (a) and $f_{x\ max}$ = ~ 190 kHz.

Frequencies were measured by the USTI and universal counter Agilent 53132A in parallel until totaling 65 measurements.

The measurement error has been evaluated from appropriate statistics characteristics. Statistical characteristics are adduced in Tables 1 and 2, and densities of distribution are shown in Fig. 9 a, b respectively. The relative error does not exceed the programmable relative error 0.0005 % in both cases.

Table 1. Statistical characteristics at $f_{x\ max}$ measurements

Parameter	Value
Minimum $f_{x\ max}$ (min), Hz	190630.952
Maximum $f_{x\ max}$ (max), Hz	191115.705
Sampling Range, $f_{x\ max}$ (max)- $f_{x\ max}$ (min), Hz	484.7524
Median	0
Arithmetic Mean, Hz	190853.372
Variance, Hz	19236.0482
Standard Deviation, Hz	138.6941
Coefficient of Variation	1376.0744
Confidence Interval at probability P = 97 %	190816.04 < f_{xmax} < 190890.704
Relative error, %	0.00019 < 0.0005

Table 2. Statistical characteristics at $f_{x\ min}$ measurements.

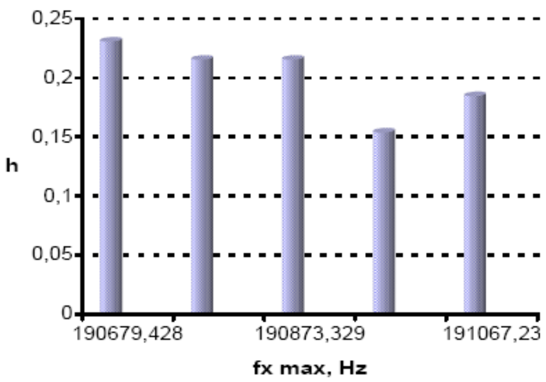
Parameter	Value
Minimum $f_{x\ min}$ (min), Hz	1831.6609
Maximum $f_{x\ min}$ (max), Hz	1832.9903
Sampling Range, $f_{x\ min}$ (max)- $f_{x\ min}$ (min), Hz	1.3294
Median	0
Arithmetic Mean, Hz	1832.2021
Variance, Hz	0.1367
Standard Deviation, Hz	0.3697
Coefficient of Variation	4955.401
Confidence Interval at probability P = 97 %	1832.1026 < $f_{x\ min}$ < 1832.3017
Relative error, %	0.0005

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 uniform population. For five equidistant classes and a probability P = 97 %, according to the χ^2 –test, $S < \chi^2_{max}$, where S is the sum of deviations between the data set and the assumed distribution and χ^2_{max} is the maximal possible allowable argument of the χ^2 distribution. Hence, the hypothesis of uniform distribution can be accepted in the both cases.

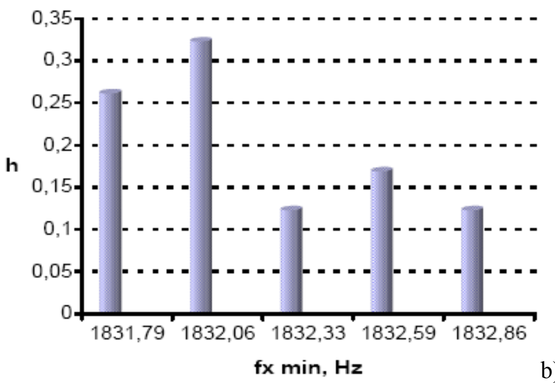
Some additional design considerations should be used at distance measuring systems design. It is a choice of IR LED and its current stabilization; composition of the target object, etc. Other design considerations are connected with mechanical issues.

An additional infrared- or visible light-to-frequency converters [2] can be connected to the second channel of the

USTI in order to extend it functionality and application areas.



a)



b)

Fig. 9. Density of distribution for $f_{x\ max}$ (a) and $f_{x\ min}$ (b) measurements.

The designed sensor system can be used for a variety of purposes, including absolute distance measurement, thickness calculation, slope and deformation control, linear distance measurement, position control, profile logging, centering control, and diameter/eccentricity measurement.

4. CONCLUSIONS

The designed measuring system demonstrates high metrological performances at minimum possible hardware and inexpensive elements costs. Performance improvements are achieved due to novel, precision modified method of the dependent count for frequency measurements with a non-redundant conversion time [10], which is used in the Universal Sensors and Transducers Interface IC.

Such measuring systems can be used also in many applications for measurement of geometrical quantities as tilt, deformation, diameter, etc. and proximity sensing applications.

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